Journal of the Royal Society of Western Australia, 76: 99-122, 1993

The mangrove systems of Western Australia: 1993 Presidential Address

V Semeniuk

21 Glenmere Road, Warwick, WA 6024

Manuscript received October 1993

Abstract

Mangroves of tropical Western Australia occur in subcontinental- to regional-scale sectors that are related to hinterland geomorphology, coastal processes and sedimentary provinces. The four main features that determine location and nature of the sectors are the style and amount of fluvial input from the hinterland to the coastal zone, the mineralogical nature of mud in the mangrove environment, the climatic setting of the coast, and the nature of the oceanographic regime that receives the sediment. From north to south the sectors are: Cambridge Gulf, with mangrove habitats in a tide-dominated estuarine-gulf environment; Kimberley Coast, with mangrove habitats in a tide-dominated ria-archipelago setting; King Sound, with mangrove habitats in a tide-dominated estuarine-gulf environment; Canning Coast, with mangrove habitats in barred to open tidal embayment settings; Pilbara Coast, with mangrove habitats in wave-dominated settings of deltas, barrier islands and ria-archipelago systems; Rowley Shelf Province, with mangrove habitats in small embayments and lagoons along the island shores and interior to islands; and Carnarvon Province, of uplifted limestone, with mangrove habitats in small embayments, deltas, and inland playas.

Within these coastal sector settings, there is a profusion of smaller scale habitats, the scale at which mangrove populations respond; these may be restricted to, and be distinctive of a particular setting. Combining the sectors with climate provides the best delineation of mangrove regions in Western Australia. This approach thus links climate [which determines species richness in a given area] with geomorphic-sedimentary setting [which determines whether habitats for particular species will be developed]. Accordingly, nine major mangrove regions are delineated on the availability of appropriate habitats and species richness in tropical Western Australia: Cambridge Gulf—semi-arid zone; Kimberley Coast—subhumid to humid zone; Kimberley Coast—semi-arid zone; King Sound—semi-arid zone; Canning Coast—semi-arid zone; Pilbara Coast—arid zone; Rowley Shelf Province—arid zone; and Carnarvon Province—arid zone.

Introduction

The diverse mangrove formations of northern tropical Western Australia inhabit a range of shore types between Shark Bay and Cambridge Gulf, and appear as a mosaic of complex systems along the coast. However, there are underlying physical patterns of geology, geomorphology, climate, coastal processes, and hydrology along this coast which help explain this complexity. My own interests in mangroves in these regions have been manifold, and the approach I have used in researching these systems has tended to be holistic and hierarchical, combining information on geology, geomorphology, sedimentology, soils, groundwater hydrology, and hinterland / shore interactions (*e.g.*, Semeniuk 1983, 1985), with ecological and biological information such as mangrove species composition, structure, physiognomy and population maintenance (*e.g.*, Semeniuk & Wurm 1987).

My research on the mangroves of Western Australia over the past 22 years has had four objectives. Firstly, to unravel the evolution of the coast from regional scale to small scale in order to understand the development of mangrove habitats in tropical Western Australia. Secondly, to relate mangrove assemblages, populations and their zonation to habitats and gradients within habitats. Thirdly, to understand some of the mechanisms that maintain mangrove populations and that control their structure and physiognomy. Fourthly, to understand the various mechanisms that determine the survivorship and physiognomy of individual mangrove trees.

The first stage in this research was to establish a framework of coastal types so that the variety of types of smaller scale units that mangroves inhabit could be determined and studied in their spatial context, and any recurring pattern of habitats could be viewed in regional to subcontinental perspective. This paper concentrates on the results of research at that larger scale, to show the subcontinental scale patterns in the mangrove systems, to determine the reason for these patterns, and to describe some of the typical suites of habitats that are generated within the larger scale coastal types. A more detailed treatment of the mangrove systems at the smaller scales, *e.g.*, within the habitats, in terms of stratigraphy, sedimentology, hydrology, mangrove population structures and floristics, is currently in preparation (Semeniuk in prep).

Information obtained at the subcontinental scale on coastal types and their suite of smaller-scale habitats for mangrove systems can be important in a number of ways—1. to understand the distribution of the different types of mangrove formations in this State, 2. as a framework for comparisons between the different mangrove systems along the coast, 3. to select coastal reserves, 4. for coastal managers to understand the types of coast and the structures and processes that make them host to mangroves, 5. to predict the effects of a potential sea level rise in response to global warming, and 6. as a framework for designating more detailed areas for further research. This approach also provides a basis for understanding species distribution and maintenance at the local scale. Also, since mangroves can be related to specific habitats, an inventory of habitats within a region can provide a valuable first indication as to what species can be expected, and where to find them, in a given area.

Material and Methods

Data in this paper are based mainly on fieldwork (*e.g.*, Semeniuk 1980a,b, 1981a,b, 1982, 1983, 1985, 1986a, in prep; Semeniuk & Wurm 1987). Coasts not surveyed directly on the ground were examined and photographed by aerial survey, then studied using aerial photographs. In the field, mangrove systems were studied along transects where trenches, cores or augers were used to determine soil sequence and stratigraphy (Semeniuk & Wurm 1987). Samples from fieldwork were processed in the following manner (Semeniuk 1983, Semeniuk & Wurm 1987): binocular microscope examination; sieving (granulometry); thin section analysis of selected samples; acid digestion to determine carbonate content within the mud fraction; x-ray diffraction of selected mud fractions for more detailed mineralogic analysis; descriptions of cores; analysis of selected shells for ^{14}C; and analysis of soilwater and groundwater for salinity. Terminology for geomorphic units, habitats and scale follows Semeniuk (1986a).

Overview of the Mangroves of Western Australia

Mangrove formations occupy extensive coastal tracts of the tropical northwestern part of Australia (Fig 1A). With a few notable exceptions, such as the cliffed rocky coasts along the tectonically uplifted Cape Range and Cape Cuvier peninsulas, and high-energy coastlines such as Eighty Mile Beach (Fig 1E), the mangroves form a nearly continuous fringe along the coast of Western Australia when viewed at the sub-continental scale. They span a climatic gradient from arid in the south to humid in the north (Bureau of Meteorology 1973, 1975; Gentilli 1971, 1972; Fig 1B) and occur in a wide range of settings and habitats (Semeniuk, 1983, 1985, 1986b). The mangroves occur in tidal regimes from microtidal in the south to macrotidal in the north (Easton 1970; Davies 1977; Fig 1C), inhabiting the interval between mean sea level (MSL) and about mean high water spring tide (MHWS) in arid to semi-arid environments, and extending almost up to the position of equinoctial high water mark (EHWS) or highest astronomical tide (HAT) in more humid climates.

Mangroves inhabit coasts located in quite variable geological and geomorphic settings (Fig 1D), and hence occupy ria shores, tidal embayments, limestone barrier coasts, wave-dominated deltas, tide-dominated deltas, and beach/dune shores, amongst others. These variable geological settings influence the relationship of hinterland to the tidal zone, and variation in this relationship, within diverse climate settings, results in differing types of hydrologic exchanges between freshwater and tidal zone hydrology. For instance, the hinterland/tidal interactions in the Kimberley area (ria coasts) contrasts with the deltaic and barrier island setting of the Pilbara region (Semeniuk 1983, 1985).

The mangroves of Western Australia occur along coasts that are also variable both in their modern dynamics (erosion vs accretion; wave-dominated conditions vs tide-dominated conditions; storm activity) and their Holocene sea level history. Many of these features are fundamental to the development of the different mangrove systems. For instance, the coast between Shark Bay and Port Hedland is wave-dominated, with wave climate due to swell and wind waves. As a result, many of the coastal landforms have been sculptured by wave and wind processes; some parts of this coast are delta-lands, others are barrier islands, others are beach/dune systems. In contrast, the Kimberley coast is tide-dominated and is of a markedly different character in terms of coastal style, with sedimentation and development of the main mangrove habitats confined to embayments.

To show the floristic, ecological and edaphic variablity, a brief description of the mangrove systems of Western Australia is presented below in terms of 1. mangrove biogeography, zonation, structure, and physiognomy as related to climatic setting, 2. regional factors important in developing mangrove habitats, and 3. types of mangrove habitats.

Biogeography, zonation, structure, and physiognomy

There are 17 mangrove species in Western Australia (Semeniuk *et al.* 1978; Semeniuk 1983); these are: *Acanthus ebracteatus* Vahl, *Aegialitis annulata* R. Br., *Aegiceras corniculatum* (L.) Blanco, *Avicennia eucalytifolia* Zipp. ex Miq., *Avicennia marina* (Forsk.) Vierh., *Bruguiera exaristata* Ding Hou, *Bruguiera parviflora* (Roxb.) Wight & Arn. ex Griff., *Camptostemon schultzii* Mast., *Ceriops tagal* (Perr.) C.B. Rob., *Excoecaria agallocha* L., *Lumnitzera racemosa* Willd., *Osbornia octodonta* F. Muell., *Pemphis acidula* J.R. & G. Forst., *Rhizophora stylosa* Griff., *Scyphiphora hydrophylacea* Gaertn., *Sonneratia alba* Sm., *Xylocarpus australasicus* Ridley (may be = *X. mekongensis* Pierre; see discussion in Tomlinson 1986). The most common and widespread species are *A. marina*, *R. stylosa*, *B. exaristata*, *C. tagal*, *A. annulata* and *A. corniculatum*.

The distribution of mangrove species in Western Australia has been recorded by Saenger *et al.* (1977), Semeniuk *et al.* (1978), Wells (1981, 1982), Semeniuk (1983, 1985), and Bridgewater (1985). Fifteen species occur in the northern, humid parts of the region and this number progressively decreases towards the southern, more arid areas down to four species in Exmouth Gulf, and only one species in Shark Bay (Fig 1F).

Mangrove formations exhibit compositional zonation across the tidal zones (*cf* MacNae 1968). This zonation depends on the type of habitat (*e.g.*, sandy tidal flat, muddy tidal flat, spit), type of physico-chemical gradient within the habitat (*e.g.*, inundation frequency, salinity, grainsize of substrate), and species pool. Variation of zonation of mangroves across the climatic regions of Western Australia

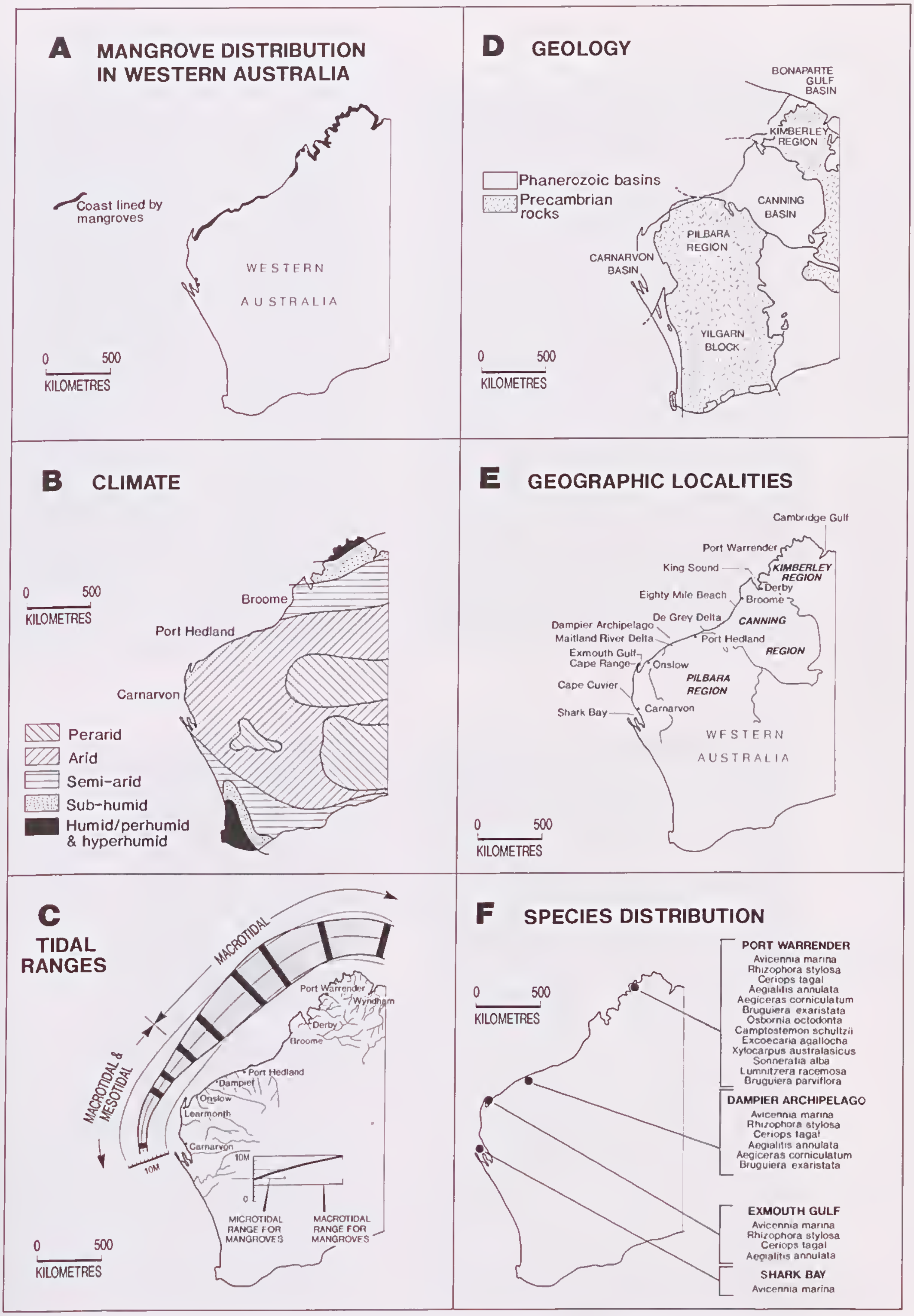


Figure 1. The subcontinental setting of mangroves in Western Australia: **1A:** Distribution of mangroves in Western Australia. **1B:** Climate setting (after Gentilli 1972). **1C:** Tidal regime (data from Calder 1979). **1D:** Geological setting (after Geological Survey of W.A. 1975), showing the variable geological provinces that the coast intersects. **1E:** Main geographic locations mentioned in text. **1F:** Change of species richness from humid northern areas to southern arid areas (data from Semeniuk *et al.* 1978)

and between habitat types across the different climatic regions of northern and northwestern Australia has been documented by Semeniuk *et al.* (1978) and Semeniuk (1983, 1985). In the species-rich tropical humid areas there is marked zonation of mangroves. For instance, on muddy tidal flats, there may be a seaward zone of *S. alba*, followed by a zone of *A. marina*, a zone of *C. schultzii* and then by *R. stylosa*, and finally a mixed landward zone of *A. marina, A. annulata, B. exaristata* and locally pure stands of *C. tagal*. In arid zones, muddy tidal flats present a more simple sequence: a seaward zone of *A. marina*, a middle zone of *R. stylosa*, and a landward zone of *A. marina*, with local pure stands of *C. tagal*.

The mangrove formations in Western Australia also are variable in their structure and physiognomy in relationship to climate and to their position on the tidal flat. Tall forest formations tend to be common in the humid regions, and scrub and heath (also termed "dwarf forests" by some authors) in the more arid regions. Physiognomically, the mangrove trees and shrubs vary from being predominantly more slender-trunked in humid forest settings to recumbent, gnarled, or mallee-form in more arid settings. The structural and physiognomic variation within the mangroves across the tidal flat follows the gradients of decreasing frequency of inundation of seawater and increasing salinity of groundwater: forests, low forests and scrub dominate seaward parts of the mangrove formations, whereas scrub and heath dominate landward parts. Thus in humid areas there is gradation from forests in seaward parts of the mangrove formations to scrub and heath in landward parts, and in arid zones from recumbent and gnarled low forests and scrub in seaward parts to mallee-form heath and "dwarf forests" in landward parts of the formations. Where there is only one species of mangrove on the tidal flat (*e.g., Avicennia marina*), there often is a physiognomic and structural zonation in the mangrove belt in response to the physio-chemical gradients.

Regional factors important for developing mangrove habitats

Regional factors that determine the style of mangrove habitats developed in a given area are coastal setting, climate, and tidal range (Table 1). These factors are of course interrelated.

Table 1

Regional factors important in the development of mangrove systems

Coastal Setting	
	Sediment types
	Stratigraphy
Climate	
	Rainfall & freshwater input
	Evaporation
	Cyclonic activity
	Temperature
	Wind
Tidal Range	
	Habitat availability
	Coastal processes

Coastal setting, *i.e.*, coastal geomorphology and geology, Quaternary geological history, the relationship of the coast to the differing types of hinterland, and the oceanographic setting, determine the basin setting for mangrove habitation, the coastal processes extant at a given site, and the types of sediments and stratigraphy that will underlie mangrove systems. These features are important in developing the edaphic setting of the mangrove habitats.

The important aspects of climate are: rainfall which determines the freshwater input into the tidal system either directly or via groundwater discharges (Semeniuk 1983); evaporation which places physiological stress on mangroves, and develops high salinity on the tidal flats; cyclonic activity which affects mangroves themselves, as well as modifies coasts and habitats; and temperature. Wind is important because it generates waves, and develops spits (as local habitats for mangroves; Figs 2A, B) and builds coastal dunes. These dunes can be important in mangrove systems: at larger scales they can develop lagoon/dune complexes and also form the ridge and swale systems of wave-dominated deltas; at smaller scales they function as reservoirs of freshwater—as a result the hydrologic interface between dunes and their junction with the tidal zone often becomes a local mangrove habitat; and mobile dunes can locally encroach upon and kill mangroves (Fig 2C).

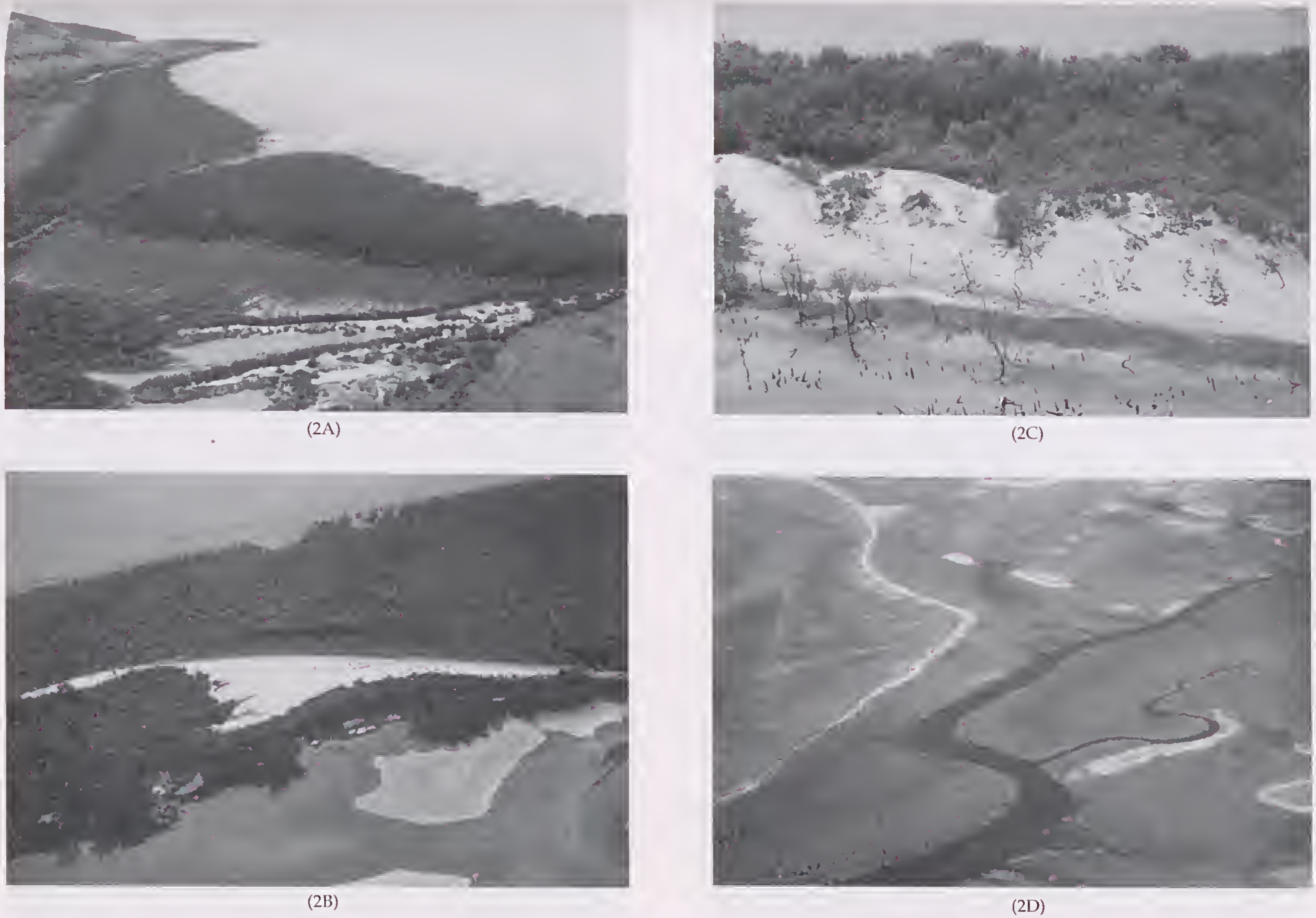
Tidal range influences the development of mangrove habitats in two ways. Firstly, the size of the tidal range determines the amount of tidal flat exposed for mangrove habitation. Secondly, the tidal range determines whether the coast will develop tide-dominated (or at least tide-influenced) coastal landforms.

As a result of all of these factors, there are developed a number of coastal systems at the regional scale that are host to mangroves in Western Australia. These include: wave-dominated deltas, tide-dominated deltas, barrier islands, tidal creek systems, embayments, ria shore and archipelago systems, dune coasts, lagoon systems, and island complexes. The occurrence of these coastal types within sectors in Western Australia are described below.

Mangrove habitats and assemblages

Within the regional-scale coastal types listed above, there is a profusion of habitat types for mangroves, many of which are restricted to a given coastal setting. Thus, for instance, in ria shore settings regardless of whether they are located in the Kimberley region or in the Pilbara, there are tidal flats, high tidal alluvial fans, rocky shores and tidal creeks. In wave-dominated deltaic settings there are lagoons in the inter-ridge swales, muddy tidal flats, sandy tidal flats and tidal creeks. Within many of the regional-scale coastal types there also may be recurring patterns of habitat types: for instance, spits, cheniers, and sandy beaches are coastal features that occur in a wide variety of regional-scale coastal settings.

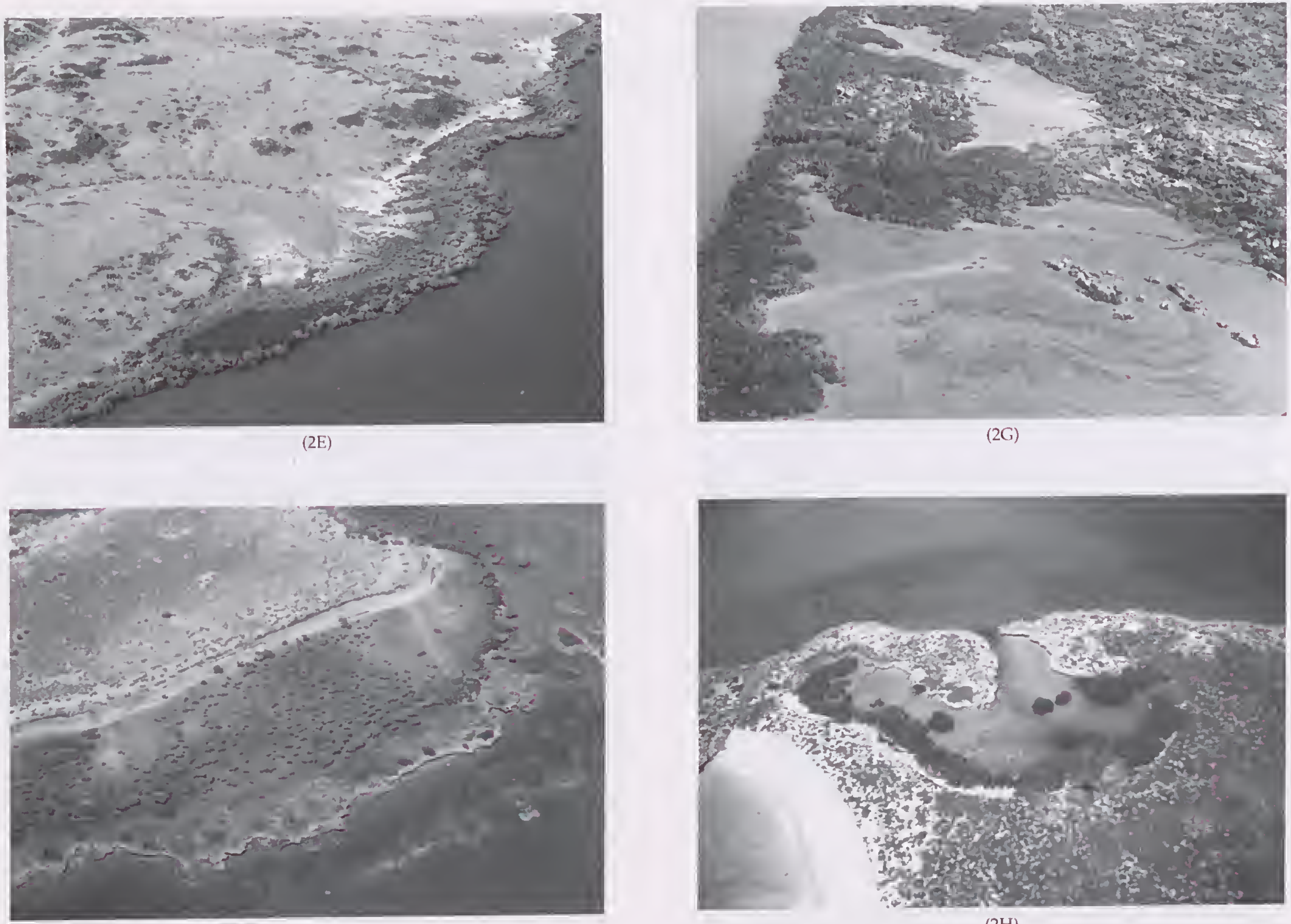
The combination of geomorphology, substrates, stratigraphy, aquifers and salinity at small scales within the regional-scale coastal types develops the various habitats for the mangroves. The main mangrove habitats in Western Australia are: muddy tidal flats, sandy tidal flats, gravelly



(2A) (2C) (2B) (2D)

Figure 2. Various small-scale habitats for mangroves, drawn from wide ranging locations, from the Kimberley Coast to the Pilbara to illustrate the wide variety and styles of mangrove habitats. **2A:** Spits, fringed by mangroves, emanating from a headland in a ria setting, Port Warrender area; also visible are zoned mangroves on the tidal flat, and tidal creek incising the tidal flat. **2B:** Spit that has encroached into a mangrove forest, perturbating the zonation; King Sound. **2C:** Shore-parallel dune belt retreating inland, burying and killing mangroves; Ashburton River delta. **2D:** High-tidal sediment aprons skirting sand islands on the high-tidal flat, and mangrove-fringed tidal creek; Onslow area.

Figure 2 continued overleaf . . .



(2E)

(2G)

(2F)

(2H)

Figure 2.—*continued* **2E:** Alluvial fan debouching onto the tidal zone; high tidal part of fan is sparsely vegetated by mangroves, but the mid-high tidal part is thickly vegetated by zoned mangroves; Dampier Archipelago area. **2F:** Limestone pavement skirting a limestone island; pavement is sparsely vegetated by mangroves; Thringa Island, Robe River delta; **2G:** Sandstone pavement cut into a sandstone hinterland; pavement is sparsely vegetated by mangroves; Mitchell River, the Kimberleys; **2H:** *Mangroves inhabiting a small embayment/lagoon; Monte Bello Islands area.*

tidal flats, spits, cheniers, rocky shores, limestone pavements, sandstone pavements, alluvial fans, banks of tidal creeks, point bars and shoals of tidal creeks, the hinterland / tidal flat contact, beaches, lagoons, sand islands, and sedimentary aprons skirting sand islands. These habitats are diagramatically illustrated in Fig 3. Some of these habitats are long-term stable, *e.g.*, rocky shores, alluvial fans, tidal flats, and sand islands, while others are dynamic, *e.g.*, spits, beaches, some tidal creeks. Selected examples of habitats are illustrated in Fig 2 to indicate typical kinds of habitats across a wide range of climatic and coastal setting; features of these habitats are described in more detail in the Figure captions.

For a given climatic region, the main mangrove habitats tend to support a distinct floristic assemblage, or at least a distinctive assemblage identified on both floristics and vegetation structure / physiognomy (Fig 4). Thus for example, a limestone pavement situated between MSL and HWN will support a different floristic and structural / physiognomic assemblage to a muddy or sandy tidal flat located between the same tidal levels. Figure 4, for instance, drawn from Semeniuk & Wurm (1978), illustrates a variety of habitats and their associated mangrove assemblages in the Dampier Archipelago area, with different compositional and physiognomic zonation evident in the different habitats.

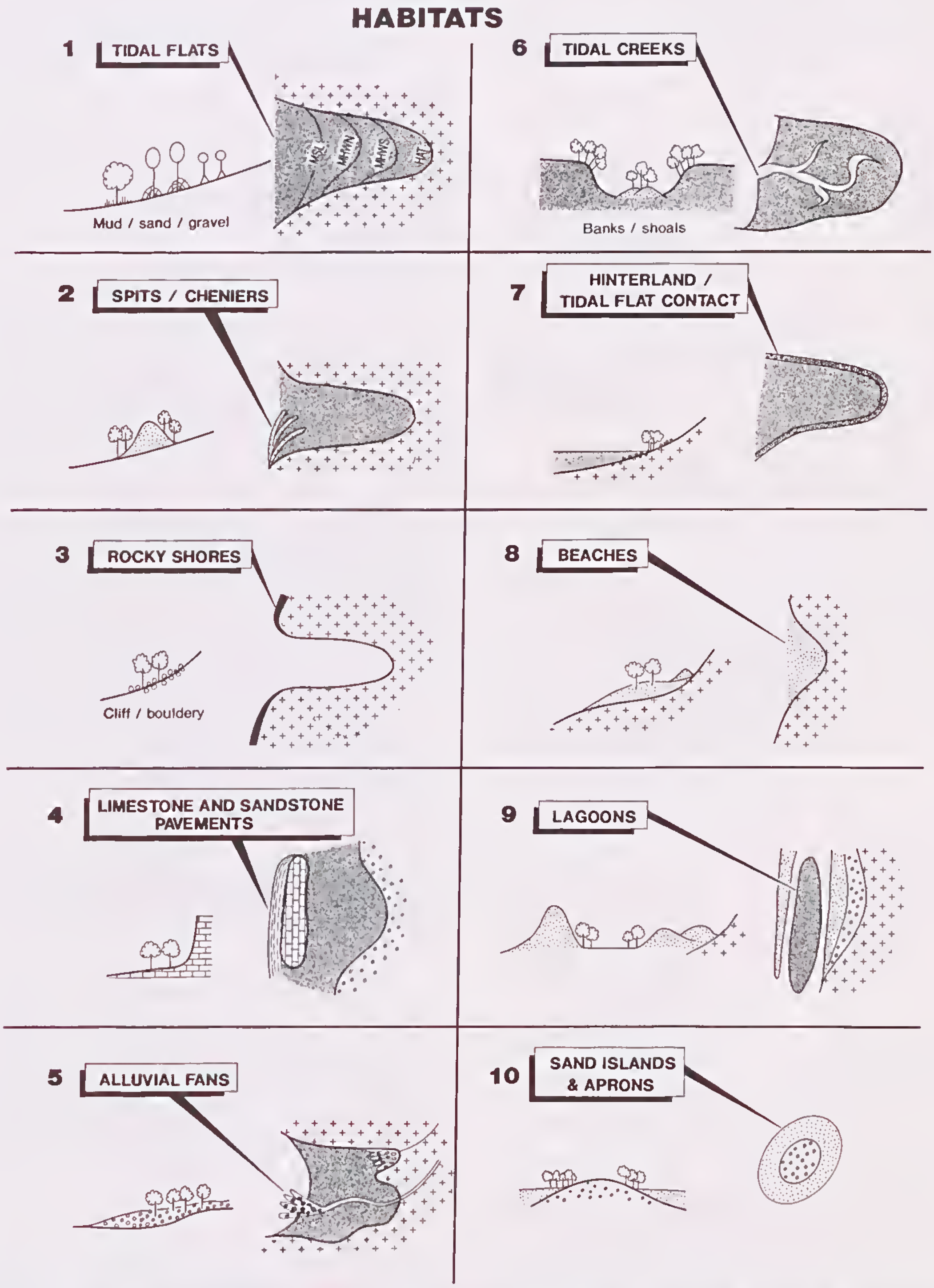


Figure 3. Diagramatic illustration of the main habitats for mangroves in Western Australia. Each type is illustrated by a plan view and a cross-section, with the location of the mangrove formation within the habitat shown.

Thus for instance, in the Dampier Archipelago area, mangroves exhibit their best physiognomic and composition zonation in the muddy tidal flat and spit (or chenier) habitats; in contrast to those on the muddy tidal flat, mangroves on sandy tidal flats are poorly zoned in terms of composition, but exhibit physiognomic zonation. This aspect of assemblages related to habitat has been previously investigated by Thom (1967), Thom *et al.* (1975) and Semeniuk (1985). A comparison between similar habitats in different climatic settings also shows that they support different floristic assemblages across the climate zones because the mangroves are drawn from differing species pools (Semeniuk 1985).

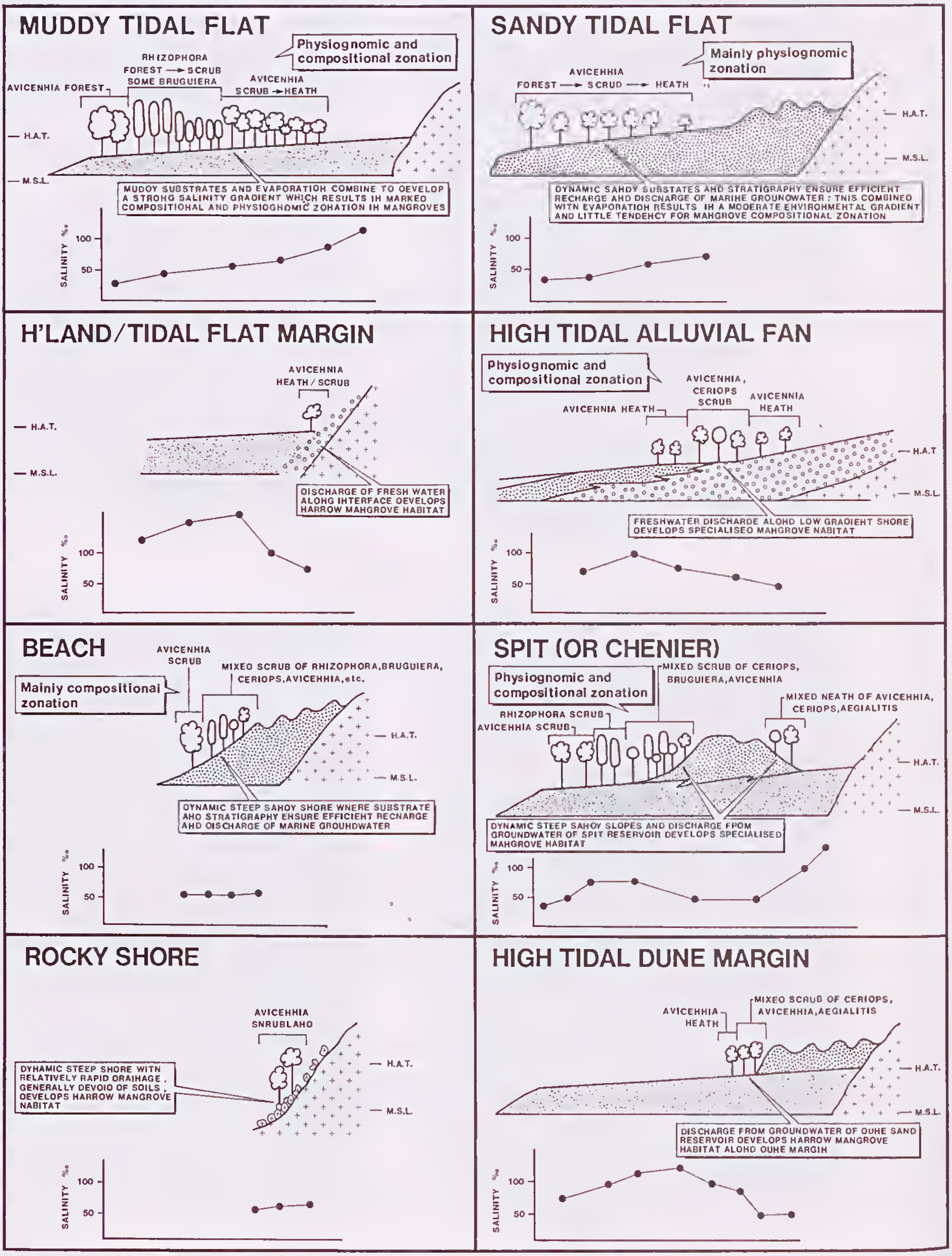

MUDDY TIDAL FLAT
Physiognomic and compositional zonation
AVICENNIA FOREST
RHIZOPHORA FOREST → SCRUB SOME BRUGUIERA
AVICENNIA SCRUB → HEATH
H.A.T.
M.S.L.
MUDDY SUBSTRATES AND EVAPORATION COMBINE TO DEVELOP A STRONG SALINITY GRADIENT WHICH RESULTS IN MARKED COMPOSITIONAL AND PHYSIOGNOMIC ZONATION IN MANGROVES
SALINITY ‰
100
50
SANDY TIDAL FLAT
Mainly physiognomic zonation
AVICENNIA FOREST → SCRUB → HEATH
H.A.T.
M.S.L.
DYNAMIC SANDY SUBSTRATES AND STRATIGRAPHY ENSURE EFFICIENT RECHARGE AND DISCHARGE OF MARINE GROUNDWATER : THIS COMBINED WITH EVAPORATION RESULTS IN A MODERATE ENVIRONMENTAL GRADIENT AND LITTLE TENDENCY FOR MANGROVE COMPOSITIONAL ZONATION
SALINITY ‰
100
50
H'LAND/TIDAL FLAT MARGIN
AVICENNIA HEATH / SCRUB
H.A.T.
M.S.L.
DISCHARGE OF FRESH WATER ALONG INTERFACE DEVELOPS NARROW MANGROVE HABITAT
SALINITY ‰
100
50
HIGH TIDAL ALLUVIAL FAN
Physiognomic and compositional zonation
AVICENNIA HEATH
AVICENNIA, CERIOPS SCRUB
AVICENNIA HEATH
H.A.T
M.S.L.
FRESHWATER DISCHARGE ALONG LOW GRADIENT SHORE DEVELOPS SPECIALISED MANGROVE HABITAT
SALINITY ‰
100
50
BEACH
AVICENNIA SCRUB
Mainly compositional zonation
MIXED SCRUB OF RHIZOPHORA, BRUGUIERA, CERIOPS, AVICENNIA, etc.
H.A.T.
M.S.L.
DYNAMIC STEEP SANDY SHORE WHERE SUBSTRATE AND STRATIGRAPHY ENSURE EFFICIENT RECHARGE AND DISCHARGE OF MARINE GROUNDWATER
SALINITY ‰
100
50
SPIT (OR CHENIER)
Physiognomic and compositional zonation
MIXED SCRUB OF CERIOPS, BRUGUIERA, AVICENNIA
MIXED HEATH OF AVICENNIA, CERIOPS, AEGIALITIS
RHIZOPHORA SCRUB
AVICENNIA SCRUB
H.A.T.
M.S.L.
DYNAMIC STEEP SANDY SLOPES AND DISCHARGE FROM GROUNDWATER OF SPIT RESERVOIR DEVELOPS SPECIALISED MANGROVE HABITAT
SALINITY ‰
100
50
ROCKY SHORE
AVICENNIA SHRUBLAND
DYNAMIC STEEP SHORE WITH RELATIVELY RAPID DRAINAGE, GENERALLY DEVOID OF SOILS, DEVELOPS NARROW MANGROVE HABITAT
H.A.T.
M.S.L.
SALINITY ‰
100
50
HIGH TIDAL DUNE MARGIN
MIXED SCRUB OF CERIOPS, AVICENNIA, AEGIALITIS
AVICENNIA HEATH
H.A.T.
M.S.L.
DISCHARGE FROM GROUNDWATER OF DUNE SAND RESERVOIR DEVELOPS NARROW MANGROVE HABITAT ALONG DUNE MARGIN
SALINITY ‰
100
50

Figure 4. Summary diagram showing key habitat features such as slope, salinity gradients, substrates, and physico-chemical processes, the resulting mangrove composition, structure and physiognomy, and the main processes of maintenance in eight environments in a ria coastal setting in the Dampier Archipelago (after Semeniuk & Wurm 1987).

The study of how habitat types relate to particular mangrove associations (with distinct floristic assemblages or structural/physiognomic types) is the baseline for predicting some of the effects of a sea level rise into heterogenous coastal systems. Within a given climatic region today, the various habitats in a coastal sector support associations of mangroves that are compositionally, structurally or physiognomically related to a specific habitat setting (Fig 4). For example, under conditions of the current sea level position, within a coastal sector in microtidal regime, there may be limestone pavements supporting simple *A. marina* scrub, a muddy tidal flat supporting zoned mangroves (from seaward to landward: *A. marina* forest, *R. stylosa* scrub, and *A. marina* scrub), and a salt flat underlain by limestone pavement. A sea level rise into a system such as this will result in more frequent inundation of the salt flat underlain by limestone pavement so that it will become a MSL-HWN limestone pavement habitat. The current association of simple *A. marina* scrub inhabiting a limestone pavement would indicate that a similar assemblage eventually should inhabit the newly formed limestone pavement after a rise in sea level.

Within each habitat type illustrated in Figure 3, there may be physico-chemical gradients in frequency of inundation, granulometry of substrates, chemistry and mineralogy of the soils, soil moisture, and salinity of soilwater and groundwater, such that there is zonation of mangroves in response to these gradients (*cf.* Semeniuk 1985, Semeniuk & Wurm 1987).

Mangrove formations in Western Australia are difficult to classify at the large to regional scale because there is much compositional and structural variation due to the mosaics of juxtaposed habitats (*cf.* Semeniuk 1985, and Semeniuk & Wurm 1987), and zoning induced by physico-chemical gradients within habitats. Elsewhere, mangrove systems, comprising fewer floristic components, have been classified into structural types, *e.g.*, the riverine, basin, fringing and dwarf categories of Lugo & Snedaker (1976) in the Carribean, but this approach has not been successfully used in Western Australia. The structural schemes (Specht 1981), or floristic schemes (Chapman 1976), used in isolation also are not successful because the former emphasises structure without using floristics, and the latter emphasises floristics without using structure in the nomenclature. The mangrove vegetation unit is a floristic-structural entity, which forms zones or mosaics across a given habitat, and its classification should consider both structural and floristic aspects; a full classification should also involve physiognomic features.

A number of authors have attempted to classify the mangrove formations in Australia (and Western Australia), using varied methods; *e.g.*, mathematical groupings using modern classification techniques (Bunt & Williams 1980), or the Zurich-Montpellier system (Bridgewater 1982), tabular sorting (Bridgewater 1985), structure (Davie 1985), assemblages-linked-to-habitats (Semeniuk 1985), and assemblages-linked-to-habitats at a first level followed by floristic-structural for units within habitat-related assemblages (Semeniuk & Wurm 1987).

The system for classifying mangroves in Western Australia at a primary level according to habitat as proposed by Semeniuk (1985) and Semeniuk & Wurm (1987) is adopted here. This approach names an assemblage after the habitat in which it occurs. Thereafter it assumes that, as there are physio-chemical variations in the habitat, structural and floristic gradation and zonation of mangroves will occur. According to this approach, the main mangrove assemblages recognised are: 1. muddy tidal flat; 2. sandy tidal flat; 3. gravelly tidal flat; 4. spit/chenier; 5. rocky shore; 6. limestone and sandstone pavemen; 7. alluvial fan; 8. tidal creek bank; 9. tidal creek shoal (or point bar); 10. hinterland fringe; 11. beach; 12. lagoon; and 13. sand islands and apron.

Some of these types are specific to certain of the larger scale geomorphic settings, whereas others occur throughout tropical Western Australia. Figure 4 illustrates the type of structure and composition of selected examples of these mangrove assemblages in the Dampier Archipelago area, *viz.*, muddy tidal flat, sandy tidal flat, spit/chenier, rocky shore, alluvial fan, hinterland fringe (colonising the hinterland/tidal flat margin), and beach.

In addition to variation in habitats both locally and regionally, there is compositional (floristic) variation regionally in response to climate. Thus, the floristic assemblages that colonise similar habitats will vary from region to region. Mangrove formations and zones within a habitat may be further classified by floristics and structure at a secondary level (*cf.* Semeniuk & Wurm 1987); individual zones within assemblages thus may classifed using the schemes of Bunt & Williams (1980), those used by Bridgewater (1982, 1985), or those used by Semeniuk & Wurm (1987).

Coastal sectors for mangrove systems in Western Australia

The tropical coast of Western Australia can be subdivided into sectors of coastal types as a basis for recognising the smaller settings for mangroves in this area. The four main features that determine location and nature of the sectors are (Fig 5): the style and amount of fluvial input from the hinterland to the coastal zone, the mineralogical nature of mud in the mangrove environment, the climatic setting of the coast, and the nature of the oceanographic regime that receives the sediment.

In relation to the *style* and amount of fluvial delivery of sediment from the hinterland to the coastal zone, six systems are recognised:

— the shoreline of the Kimberley Plateau region, where a series of short rivers drain an uplifted plateau in a humid to semi-arid climate; the coast abuts the edge of the plateau; sediment input is not a major factor in coastal development, but sediment delivery is terrigenous material;

— the large funnel-shaped King Sound and Cambridge Gulf, formed where the post-glacial marine transgression has inundated large valley tracts developed by a series of major rivers in the region; these rivers have cut valleys along major geological contacts; the riverine tracts occur today in a semi-arid climate; sediment input is a major factor in Holocene coastal accretion, and sediment delivery is terrigenous material;

— the shoreline of the seaward edge of the Great Sandy Desert (Canning Basin), where there is negligible to no

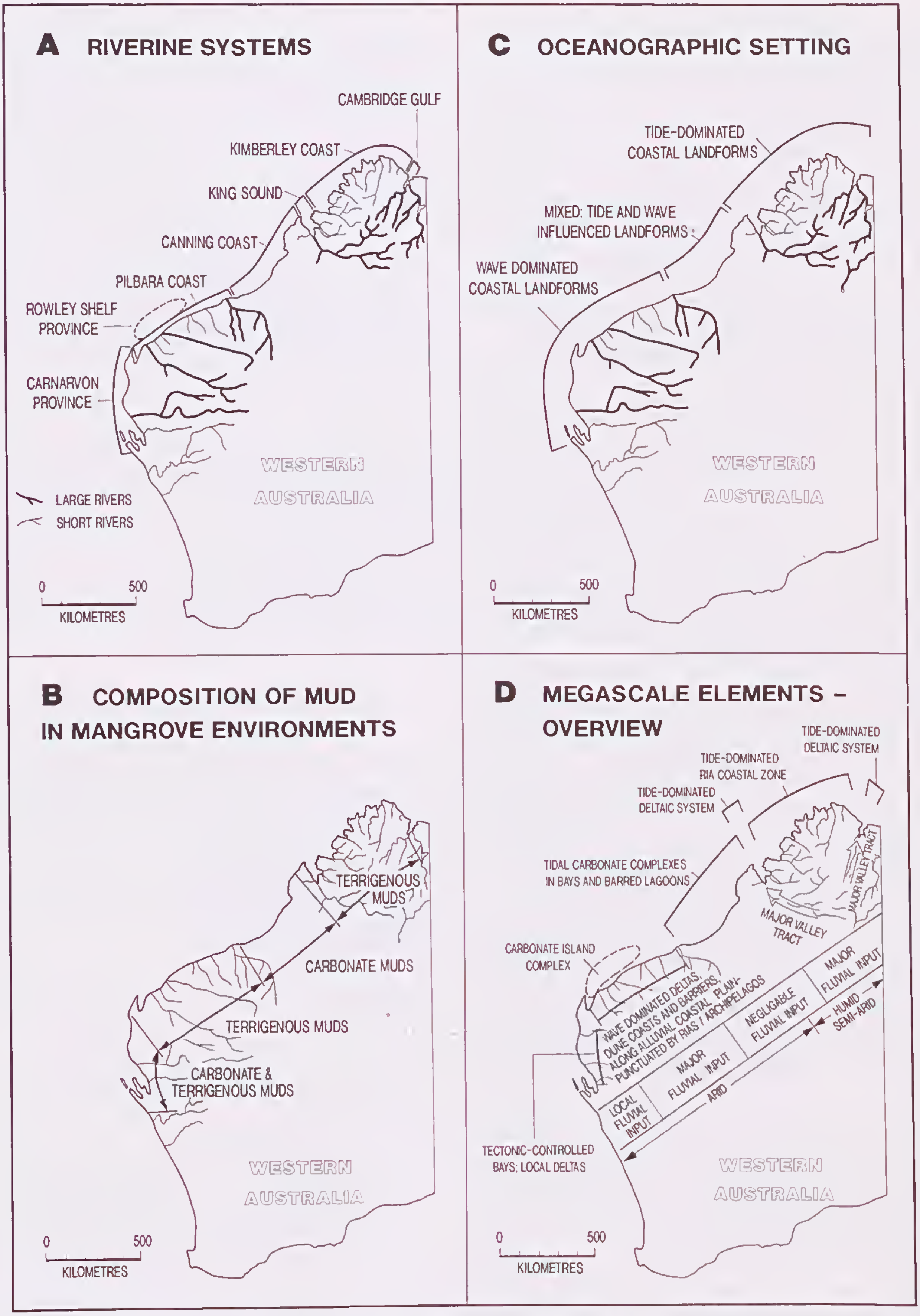


Figure 5. Background information relevant to the coastal sectors in northwestern Australia. **5A:** The riverine systems, showing the large and short rivers in the systems. **5B:** The composition of mud in mangrove environments. **5C:** The oceanographic setting, ranging from wave-dominated in the south to tide-dominated in the north. **5D:** The overview of the coast of northwestern and mid-western Australia showing the important elements of riverine setting, oceanographic setting, composition of mud, and resultant coastal features at the megascale.

fluvial delivery to the coast, and the fine-grained coastal sediment is predominantly carbonate;

- the coast of the Pilbara region where a series of large to medium-sized rivers drain an inland high-relief hinterland in an arid climate and have built a broad, low coastal plain; sediment input is not a major factor in the Holocene, but over the full period of the Quaternary, it has been a major factor in developing the coast; sediment delivery is terrigenous material;
- the system of the oceanic islands offshore from the Pilbara coast; suspended mud from river floods reach these oceanic islands to accumulate in protected areas; sediment input is not a major factor; sediment delivery is terrigenous material; the system of the tectonically complex Carnarvon Basin area where large rivers drain the arid Pilbara uplands and discharge into barred lagoons or into the marine environment; there is a mix of fluvial input and locally derived carbonate sediment, dependant on whether the local system is supplied with or starved of fluvial sediment.

In relationship to the mineralogy of mud found in the mangrove environment, three types are recognised:

- those coasts that are comprised dominantly of terrigenous mud, composed of kaolin and quartz clay and silt, with minor or subordinate amounts of locally derived carbonate mud; these areas are downstream from the zones of major fluvial systems—they are the coastal zones downstream from the Kimberley and Pilbara regions, and include the offshore islands that receive mud in suspension from the the Pilbara river floods;
- a coast that is comprised dominantly of carbonate mud; being starved of all but very minor fluvial sources, there is no opportunity to deliver significant terrigenous mud to the shore; this system comprises the shoreline of the Canning region;
- a system that is mixed: some parts are of terrigenous mud, where rivers have breached to the coast, and some dominantly of carbonate mud; this system is within the tectonically active Carnarvon Basin.

In regards to climate, there are three types of settings:

- a humid to subhumid climate in the Kimberley region; a semi-arid climate in the area of King Sound, Cambridge Gulf, and part of the Canning region; an arid climate in the Pilbara, the oceanic island system, and the Carnarvon region.

In relationship to oceanography, there are three types of systems:

- a tide-dominated system, with macrotides in King Sound, Cambridge Gulf, and the Kimberley region; in this system deltas are tide-dominated forms;
- a mixed tide-influenced and wave-influenced system along the coast of the Canning region, where the tidal regime is macrotidal, but wave processes are still effective in developing coastal landforms;
- a wave-dominated area, but within which the tide regime varies from microtidal in the south to macrotidal in the north, in the Pilbara, the oceanic islands system on the Rowley Shelf, and the Carnarvon region; deltas in these systems are wave-dominated forms.

In combination, these regional features develop seven coastal sectors. From north to south, these sectors and a summary of mangrove habitats within them are (Figs 6 & 7):

1. **Cambridge Gulf**, with mangrove habitats in a tide-dominated deltaic-estuarine environment in a gulf setting where the mud component of the sediments is dominantly terrigenous;
2. **Kimberley Coast**, with mangrove habitats in a tide-dominated ria-archipelago setting where terrigenous mud is dominant where the mud component of the sediments is dominantly terrigenous;
3. **King Sound**, with mangrove habitats in a tide-dominated deltaic-estuarine environment in a gulf setting where the mud component of the sediments is dominantly terrigenous;
4. **Canning Coast**, with mangrove habitats in a barred to open tidal embayment settings where the mud component of the sediments is dominantly carbonate;
5. **Pilbara Coast**, with mangrove habitats in wave-dominated settings of deltas, beach/dune coasts, limestone barrier islands, and ria-archipelago shores; the mud component of the sediments is dominantly terrigenous;
6. **Rowley Shelf Province**, with mangrove habitats in small embayments along the wave-dominated island shores and in lagoons of the island interiors; the mud component of the sediments is dominantly terrigenous; and
7. **Carnarvon Province**, of uplifted Tertiary rocks, with mangrove habitats along the coast in small embayments, lagoons, and wave-dominated deltas, and inland in saline playas; the mud component of the sediments is dominantly terrigenous or carbonate, dependant on setting.

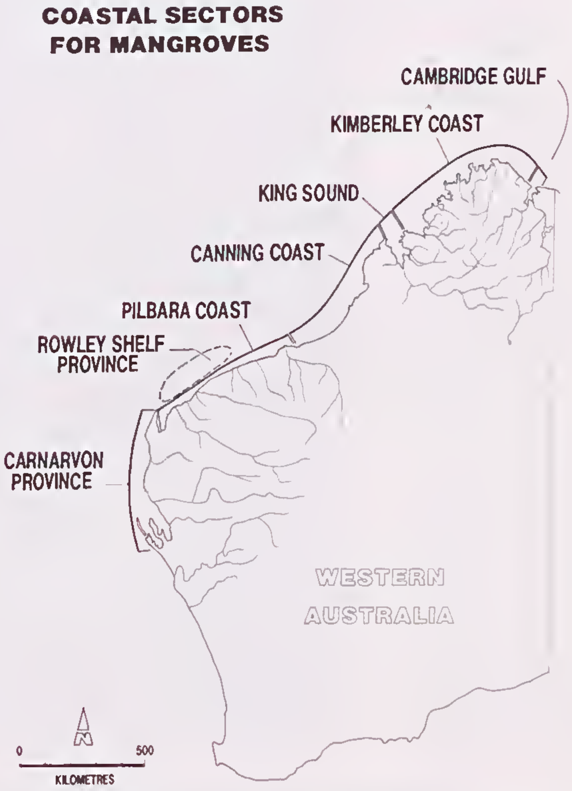


Figure 6. Coastal sectors for mangrove systems in northwestern Australia, from information presented in Fig **5D**.

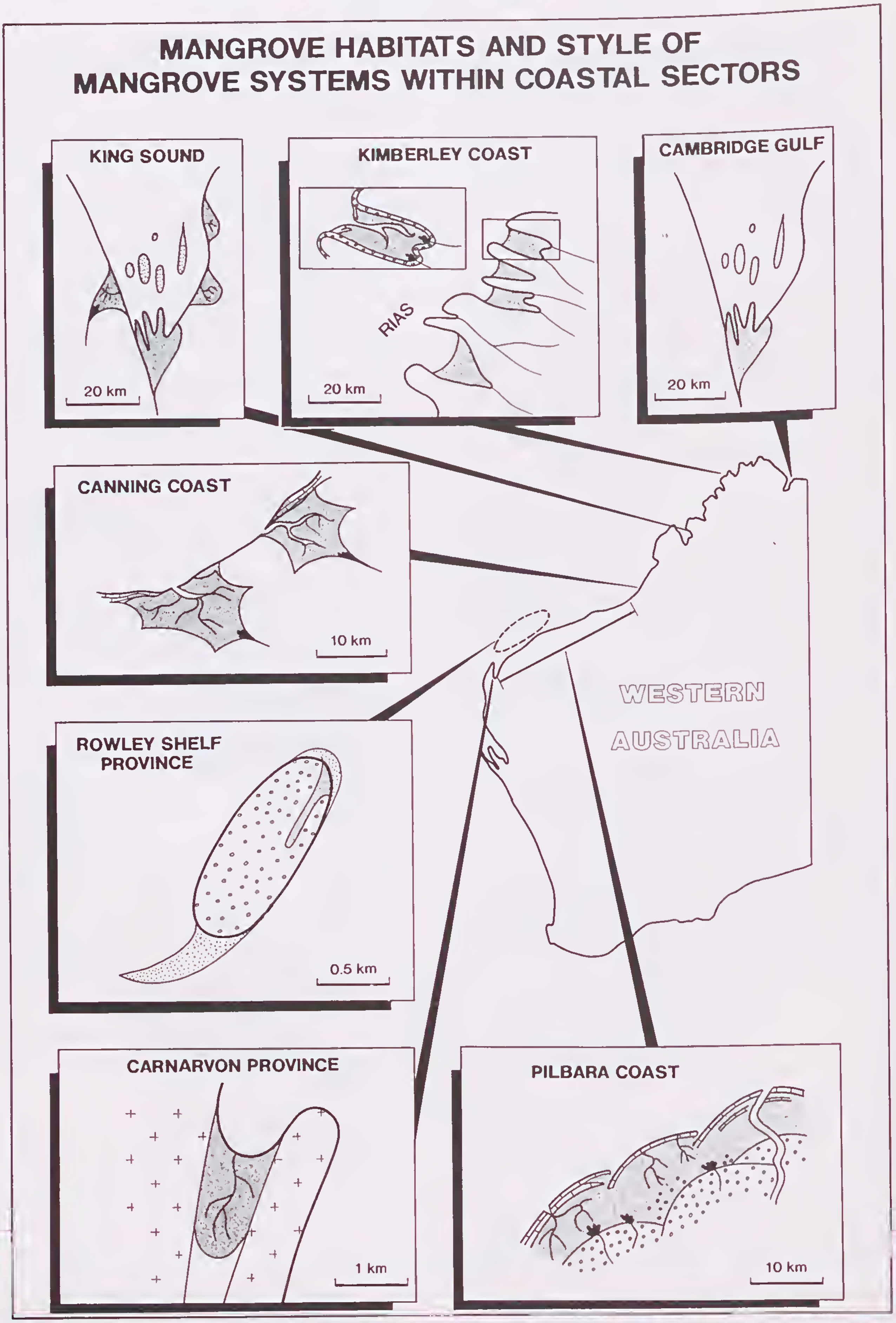
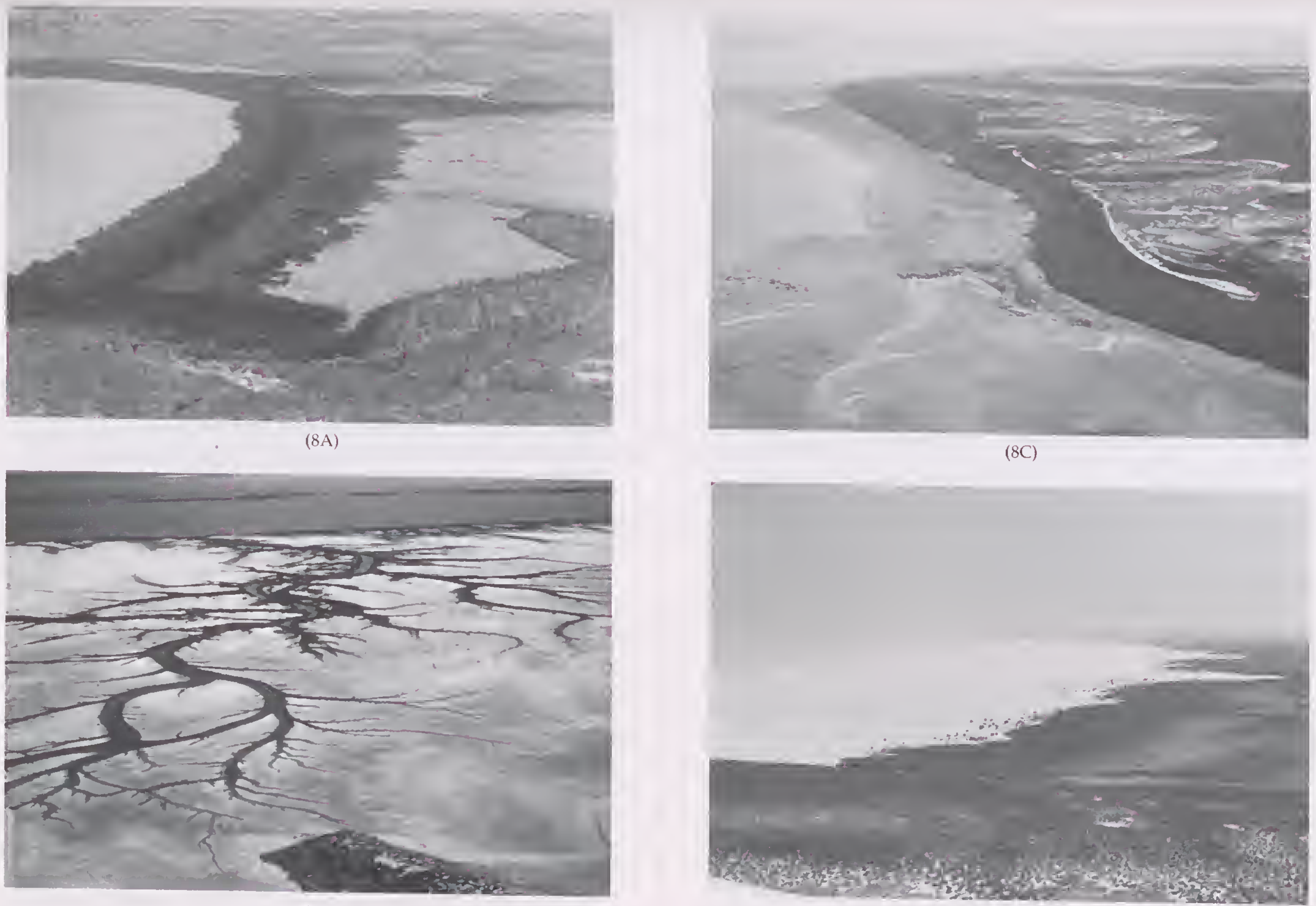


Figure 7. Summary of mangrove habitats and style of mangrove systems within the coastal sectors. Each coastal sector has a distinct style of coastal form and distinct suites of mangrove habitats as discussed in the text.



(8A)

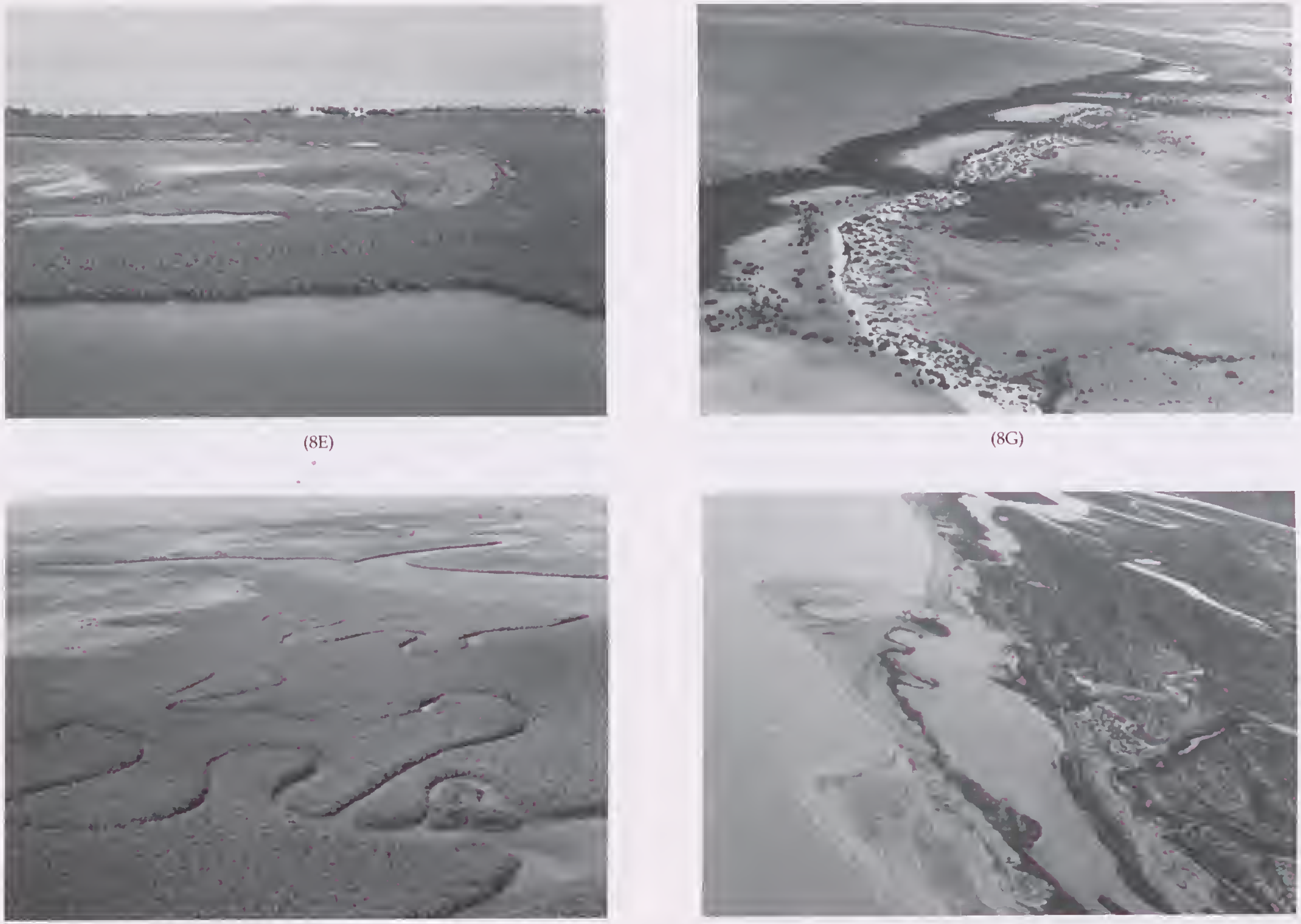
(8C)

(8B)

(8D)

Figure 8. Aerial photographs showing typical views of mangrove systems in the coastal sectors, proceeding from the Kimberley Coast in the north to the Carnarvon Province in the south, to illustrate the variation in mangrove systems within each of the coastal sectors. **8A:** Zoned mangrove on tidal flat, Port Warrender area, the Kimberley Coast; salt flat landward of the mangroves, and a hinterland fringe of mangrove are also evident. **8B:** Mangrove-fringed tidal creek traversing a broad salt flat, King Sound. **8C:** Coast cut into a linear dune field to develop spits from the dune tips; mangroves fringe the coast in front of eroding spit line; King Sound. **8D:** Simple mangrove formation of *Avicennia marina* inhabiting broad tidal embayment; white nature of carbonate tidal mud is evident; Roebuck Bay, Canning Coast.

Figure 8 continued overleaf . . .



(8E)

(8G)

(8F)

(8H)

Figure 8.—*continued* **8E:** Limestone barrier fringed by mangrove; Yammedary Island, Pilbara Coast; **8F:** Tidal creeks meandering through mangrove vegetation; Weld Island area, Pilbara Coast; **8G:** Mangroves lining the coast, succeeded to landward by a line of cheniers and further to landward by a salt flat; tidal creek headwaters incise into the line of cheniers; Regnard Bay area, Pilbara Coast. **8H:** Mangroves inhabiting depressions between beach ridges, Gascoyne delta, Carnarvon Coast (photograph: D P Johnson).

Each of the coastal sectors has a distinct range of large-scale coastal landforms, and local geomorphic and sedimentary patterns (Figs 7 & 8). Within the coast types there also are a profusion of smaller-scale habitats, the scale at which mangrove populations respond; these may be restricted to, and distinctive of a particular setting. Figure 7 illustrates for each of the coastal sectors, the style of mangrove habitats present within them. Thus, for instance, King Sound and Cambridge Gulf are both large funnel-shaped embayments within which tide-dominated coastal features are evident. The Canning Coast is composed of small embayments that are incised by tidal creeks and semi-barred by spits or limestone ridges. The Pilbara Coast is a complex of deltas, barrier islands, older Pleistocene deltas and local alluvial fans, with incision of the system by tidal creeks. The small islands set in the Rowley Shelf system have, along their periphery, spits, small lagoons and beaches developed as mangrove habitats. In parts of the Carnarvon Province, mangrove habitats are developed in embayments between tectonically uplifted bedrock ridges. Figure 8 exhibits some typical views of the various coastal sectors, proceeding systematically from the Kimberley Coast to the Carnarvon Province, to illustrate the variability of the mangrove systems.

A brief description of the sectors in terms of their geological setting, the dominant processes therein, and the range of small-scale mangrove habitats is presented below. Tidal information for the different locations is from Calder (1979).

Cambridge Gulf Cambridge Gulf is a large gulf with a tide-dominated delta at its head (Thom *et al.* 1975), that has a semi-arid climate. It is located along the structural edge of the Kimberley Block, and is a marine-inundated valley tract that has been scoured out by large rivers of the region. The hinterland is composed of uplifted Precambrian sedimentary rocks flanked by aprons of alluvium. The tidal deposits that partly fill the gulf are sand overlain by mud. Tides are semidiurnal and macrotidal, with a mean spring tidal range of 6.6 m (Wyndham), and a maximum range of 9.1 m. The system is tide-dominated, but the large fetch of the north-south oriented gulf results in the generation of local wind waves that effect sand transport and the building of wave-built features such as spits and cheniers. Periodic storms also result in the building of cheniers that face the direction of the large fetch (Thom *et al.* 1975). Within this system, the mangrove habitats are broad tidal flats, spit/chenier systems, and large-scale to small-scale tidal creek banks and associated sediment islands and shoals (Thom *et al.* 1975).

Kimberley Coast The Kimberley Coast fringes the dissected Kimberley Plateau which is composed of uplifted Precambrian rock. The area is set in a subhumid to humid environment. Tides are semidiurnal and macrotidal, with a mean spring tidal range of 6.4 m and a maximum range of 8.6 m (Port Warrender). The coastal system has formed by marine flooding of the dissected hinterland to develop a steeply indented shore and island complexes. As such, there is an inter-gradational range of ria shores and archipelagos. At the regional scale, the Kimberley coast shows the following coastal types: ria coasts, with narrow embayments, broad embayments, straight coasts and islands; tidal-land connected islands; and archipelagos, whose margins have the same suite of units as ria coasts; sediments fill the head of ria embayments, but the outer parts of the rias are largely sediment-depauperate. Tidal sediments filling the embayments and rias are sand overlain by mud, or locally totally mud (Semeniuk 1983, 1985). Within the various large-scale embayments there is a recurring suite of mangrove habitats including tidal flats, tidal creeks, spits, alluvial fans, rocky shores and hinterland margins (Semeniuk 1985), and locally, sandstone (tidal) pavements (Figs 2A, G, Fig 8A).

King Sound King Sound, comprised of the Fitzroy River estuary and Stokes Bay, is a large gulf with a tide-dominated delta at its head (Jennings & Bird 1967; Jennings 1975; Semeniuk 1981a), similar to Cambridge Gulf. The area has a semi-arid climate. Tides are semidiurnal and macrotidal, with a mean spring tidal range of 9.8 m and a maximum range of 11.5 m (Derby). The gulf is a marine-flooded former broad valley scoured out by large rivers which have selectively eroded the structural junction between Precambrian and Mesozoic rocks. The hinterland immediately surrounding King Sound is mainly of Mesozoic rock overlain by Quaternary linear dunes, but the northern boundary is of Precambrian rock.

The system is tide-dominated, and as in Cambridge Gulf, the large fetch of the north-south oriented gulf results in the generation of local wind waves that effect sand transport and the building of wave-bulit features such as spits and cheniers. Periodic storms also result in the building of spits and cheniers that face the direction of the large fetch. Holocene tidal deposits that partly fill the gulf are sand overlain by mud (Semeniuk, 1981b), and these truncate and overlie the linear dune system (Jennings 1975). Most of the tidal land in this area is eroding on a large scale (Jennings 1975, Semeniuk, 1981a), and the various coastal features in the King Sound are products of this process. In northern areas the dune fields are truncated and develop spits along the erosion line (Fig 8C). The tidal zones of King Sound have been classed according to geomorphology into 7 types (Semeniuk, 1981a): depositional flats, unconformity flats, shoal flats, spit/chenier flats, rocky shores, mid-gulf shoals and islands. These units also form the basis of the main mangrove habitats in this sector, which include broad tidal flats, spits (Fig 2B) and cheniers, large-scale to small-scale tidal creek systems (Fig 8B) and associated shoals. Much of the mangrove zonation is related to the style of erosion along the coast, since erosion determines the type of geomorphic surface (Semeniuk 1980a).

Canning Coast The Canning Coast sector is the shore cut into the Canning Basin and it forms the seaward edge of the Great Sandy Desert. This sector has a semi-arid climate. Tides are semidiurnal and macrotidal, with a mean spring tidal range of 8.2 m and a maximum range of 11.0 m (Broome). Although the system is macrotidal, the coastal regime is both wave- and tide-influenced. Wind is an important factor in coastal processes in that it is responsible for developing dune coasts, and wave-developed coastal landforms such as spits that emanate from headlands.

In terms of sediment types, the important feature of this sector is that there are no major river outlets into the marine environment, and little or no fluvial run-off from a predominantly desert dune hinterland. Hence mud derived from terrestrial sources is negligible, and carbonate mud on tidal flats is characteristic of the sector. The settings of the mangrove habitats in this area have formed mainly by pre-Holocene processes: erosion of Mesozoic rock and Cenozoic aeolian hinterland has formed shallow valleys, and these have developed into a series of scalloped embayments now partly filled with mud and vegetated by mangroves. Locally, barrier spits and dunes have formed at the headlands of the embayments. Headwaters of the embayments receive some fluvial sediment which locally accumulates as sandy alluvial fans. Erosion is currently dominant in this sector, and all the mud-filled embayments have been trimmed back to expose the bedrock of their flanking headlands.

The Canning Coast between Cape Bossut and Cape Leveque exhibits a recurring geomorphic pattern of open bays and bays barred by dunes and ridges. The suite of coastal types are:

— large scale "v-shaped" bays, with smaller "v-shaped" margins; these bays are comprised of carbonate mud in upper tidal parts and sand in lower tidal parts;

— a system or series of Quaternary (Pleistocene to Holocene) sandy or limestone barriers, beach ridges, and spits, usually along the southern/southwestern portion of large scale bays—these result in the formation of a southern shore complex consisting of an "en echelon" series of smaller barred embayments (which are similar to the large-scale bays in terms of geometry and sediment systems); and

— scalloped, "v-shaped" interfaces between the high tidal zone and the hinterland.

The reasons for these recurring patterns are the "basement" geological control of disposition of headlands and their associated embayments, the regional oceanographic processes that resulted in longshore (generally northward) sediment transport, the formation of Quaternary barrier structures that emanate from headlands and protruding sections of the sandy hinterland (these barriers then shelter smaller bays and lagoons), and ancestral drainage lines—these are truncated at their seaward edge by the shore, but continue to function as sites of discharge of freshwater and alluvial sediment to tidal flats.

Eighty Mile Beach is part of this sector. Although there are no mangroves along the seafront there, mangrove mud is locally exposed along the eroding beach-face indicating that the coastal dune barriers are retreating over former mangrove environments/ deposits, and that the extent of mangrove along this portion of coast was greater earlier in the Holocene. Inland from this coast is *A. marina* as reported by Beard (1967).

Tidal flats in the region are of two types: sand-dominated flats that occur on the open coasts, and mud-dominated flats that occur typically in the various bays. Mangroves are best developed in the embayment settings (Fig 8D), and inhabit tidal flats, tidal creek systems, local spits, and (stranded) inland depressions and creeks.

Pilbara Coast The Pilbara Coast is the most varied of mangrove coasts in northwestern Australia. The unifying feature of this coastal sector is that it is a sedimentary repository for a range of rivers that drain a high-relief Precambrian rocky hinterland. The rivers discharge sediments along a coastal plain (the Abydos, Onslow and Yannarie coastal plains; Beard, 1975) that fronts a wave-dominated environment in an arid climate. The combination of fluvial and shoreline accretion processes, coastal cementation, coastal erosion, and ancestral landform architecture (such as residual limestone ridges and large outcrops of Precambrian bedrock) inherited from the Pleistocene and older periods, has produced a laterally heterogeneous coastal system (Semeniuk 1993).

Prevailing winds develop coastal dunes, and influence the construction of coastal sediment bodies by wind waves (Semeniuk & Wurm, 1987). Cyclones are common (Coleman 1971, Milton 1978; Lourenz, 1981), causing flash flooding, marked river discharge of sediment into the coastal plain, accumulation of spits in the coastal zone, and erosion and dispersion of coastal sediment bodies. Long-period swell, local wind waves, landbreeze/seabreeze systems and thunderstorms contribute to develop wave-dominated coastal landforms such as deltas, beaches, spits and bouldery shores (Steedman, 1985; Steedman & Colman 1985; Semeniuk, 1985; Semeniuk & Wurm, 1987). Tides along the Pilbara coast are semi-diurnal, with mean spring tidal ranges varying (south to north, *i.e.*, Onslow to Port Hedland) from 1.8 m to 5.8 m, and maximum tidal ranges varying from 2.8 m to 7.8 m (Easton 1970).

The Pilbara coastline is dominated by deltas, barrier coasts associated with inactive deltas, limestone barrier coasts and their associated protected lagoons and embayments, intervening bays formed where barriers have eroded to expose the formerly protected mud-floored lagoons, and archipelago-ria shores. Within these there is a multitude of varied large-, medium- and small-scale coastal landforms and sedimentary deposits such as limestone islands/barriers, spits, cheniers, sand mounds and shoals, sand aprons around islands, alluvial fans, tidal creeks, etc, often specific to a particular coastal setting (Figs 2D, E, F, Fig 8E, F, G).

Wave-dominated, active deltas occur in discrete locations in this region. Within the deltas are prodelta sediment veneers, delta front sand flats, shoals and spits, plains of shore-parallel sand ridges, strandplains with mangrove-vegetated mud-floored lagoons, mud flats with cheniers, systems of active to inactive channels, gravel flats and gravel ridges, and wide, extensive high-tidal plains, underlain by mud, which become hypersaline salt flats. Beach/dune shores are composed of beaches, beach ridges, high relief sand dunes, mobile crescentic dunes on the tops of the dune plain, interdune swales and linear, mangrove-vegetated, mud-veneered depressions, and mangrove-lined inlets formed by tidal creek erosion of the dune belt. Inactive eroding deltas, and their barriers, combine the elements of active deltas and of beach/dune shores, with the result that barriers of limestone, or gravel ridges, or sandy ridges often are laterally associated with, or form the seafront to them. As with the active deltas, the delta plain in these systems commonly is a high-tidal mud flat, or locally a sand flat, which becomes an extensive hypersaline salt flat.

Limestone barrier coasts have prominent ridges of Pleistocene limestone forming a shore-parallel barrier (or barriers) protecting muddy embayments/lagoons that are dissected by tidal creeks and vegetated by mangroves. Erosion is dominant here, with sea-front erosion of the barriers, tidal creek erosion of mud deposits leeward of barriers, and salt weathering in high-tidal environments. Limestone barriers

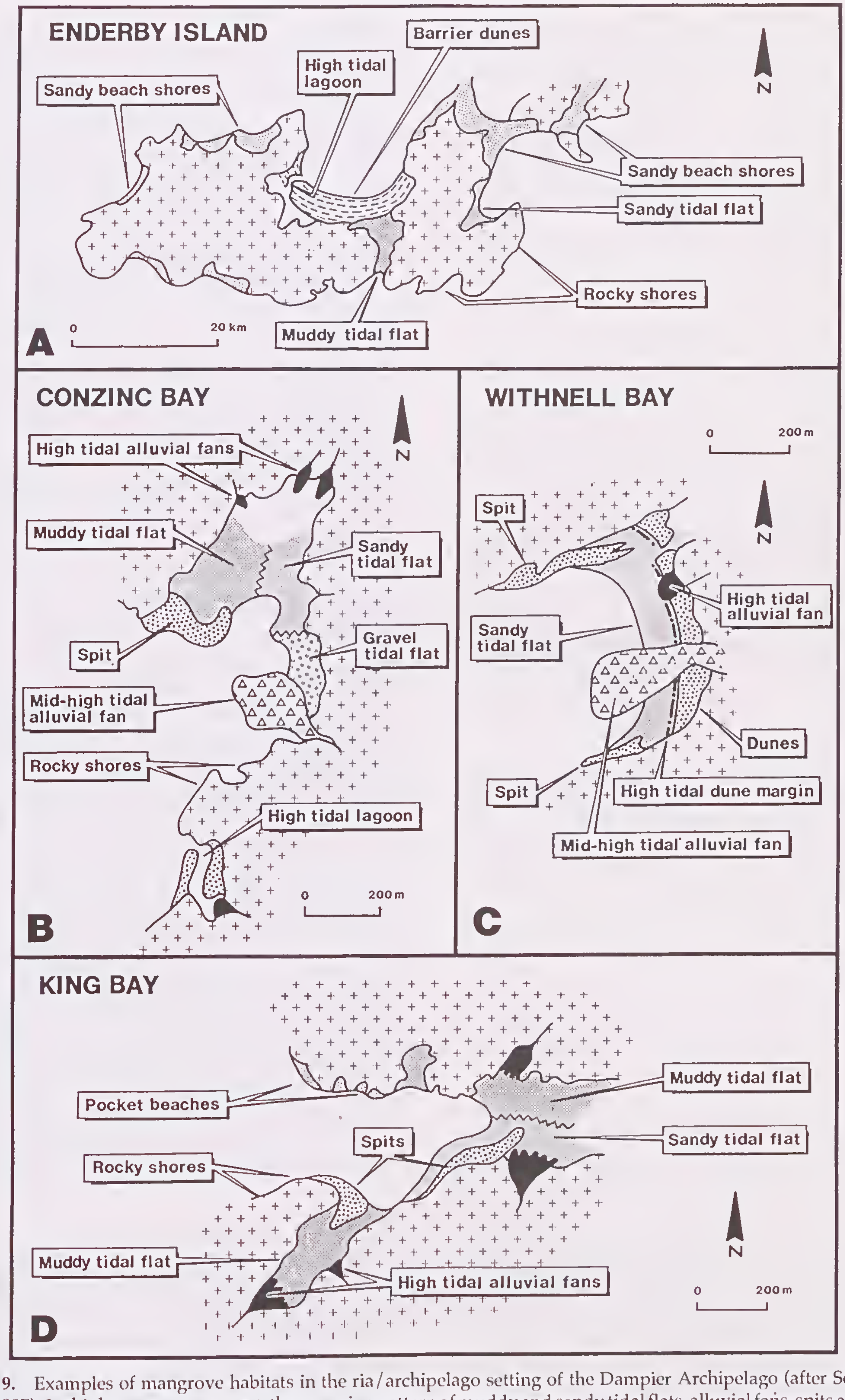


Figure 9. Examples of mangrove habitats in the ria/archipelago setting of the Dampier Archipelago (after Semeniuk & Wurm 1987). In this heterogeneous coast, the recurring pattern of muddy and sandy tidal flats, alluvial fans, spits and beaches are evident. The heterogeneous array of habitats results in a heterogeneous array of mangrove assemblages.

erode to the extent that they expose the leeward mud deposits to form eroding mud coasts fringed at the seafront by mangroves, extensive hypersaline salt flats (*i.e.*, the high-tidal surface of the former embayment), and mangrove-fringed tidal creeks.

Archipelago / ria coasts occur where Precambrian bedrock crops out at the shore. Fracture patterns and dispositon of resistant rocks determine the orientation and location of valleys and ridges of the pre-Quaternary topography (Semeniuk *et al.* 1982). Marine inundation of this terrain has formed a gradational suite of isolated scattered small islands, islands interconnected by tidal lands of sand or mud, and dissected large islands that retain "rias" along their margins. Mangrove environments in this setting include tidal flats, spits, beaches, dunes, tidal creeks, rocky / bouldery shores, high tidal alluvial fans, and sediment aprons along the upland margin (Fig 9; Semeniuk & Wurm 1987).

A number of causative factors contribute to the development of regional scale coastal types in the Pilbara system. Most of the coast has been built by a combination of deltaic and alluvial fan accretion, alternating with coastal retreat / erosion that either has built barriers or has developed scalloped bays. This pattern has been built around and upon extensions of hinterland bedrock outcrops. The main causative factors are:

—fluvial construction to develop alluvial fans and delta lands along the broad margin of the Pilbara uplands; this has been the main factor in building the coastal plain;

— destruction of deltas to develop barrier coasts and associated bays;

— longshore transport away from active deltas, and onshore aeolian activity, concommitant with delta land construction, to build coastal dune belts;

— Pleistocene limestone barrier ridges formed as aeolian accumulations along former shorelines, or formed by destruction of Pleistocene deltas;

— continuing coastal erosion to remove limestone ridges of barrier coasts and to develop scalloped, embayed coasts; and

— outcrops of Precambrian bedrock, extending from the hinterland into the coastal zone, to form archipelagos and scattered islands.

These coastal processes and features occur in different parts of the Pilbara Coast. For example, the Turner, Maitland and De Grey rivers have built active deltas, and bedrock outcrop forms the Dampier Archipelago and the Point Sampson—Cossack area (Semeniuk *et al.* 1982; Semeniuk & Wurm 1987). The barrier coasts and deltas are intergradational (since deltas with wave destruction develop into barrier systems), and this intergradational suite forms the predominant seafront architecture of the Pilbara Coast. Thus the Pilbara Coast can be viewed as a coastal plain of alluvial and tidal flat sediments, with a system of nearly continuous stretches of limestone and Holocene dune barriers, behind which are protected embayments, lagoons and tidal flats. This prevalent pattern is disrupted locally by deltas, or by bedrock outcrops.

Rowley Shelf Province The islands of the Northwest Shelf between Exmouth Gulf and Dampier Archipelago comprise the Rowley Shelf Province. They occur in an arid, oceanic setting. Tides are semidiurnal with a mean spring tidal range of 2.5 m and a maximum range of 3.6 m (Barrow Island). Five types of islands are recognised: Tertiary limestone island(s); Pleistocene oolitic limestone islands; Pleistocene aeolianite limestone islands; Holocene sand islands; and residuals of eroding deltas. The shoreline of islands tends to be armoured with beach rock formation that stabilises the islands against ersoion. Local small embayments, lagoons, sheltered beach bays, sites leeward of spits, depressions interior to the islands, and limestone pavements constitute the main mangrove habitats in this system.

Carnarvon Province The Carnarvon Province is part of the modern Carnarvon Basin (Logan *et al.* 1970; Geological Survey of Western Australia 1975) and is set in an arid climate. This system contains mangrove environments in coastal and inland settings, with the majority of mangroves in the coastal settings. The coast of this province is microtidal with mean spring tidal ranges of 2.1 m and 0.9 m and maximum ranges of 3.0 m and 1.4 m recorded at Learmonth and Carnarvon, respectively. Most of the coast is wave-dominated.

This sector exhibits considerable heterogeneity because of its strong tectonic history in the Cenozoic. North-trending uplifted anticlinal structures, composed of Tertiary sedimentary rocks, are common in the region, and as a result, there is a complicated array of ridges and local uplands, separated by lowlands and grabens. One of the prominent depositional lowlands is termed the Bullara Sunkland (Logan *et al.* 1970) and is the site for the Shark Bay system, Lake Macleod and part of Exmouth Gulf. The ridges of uplifted rock influence the location of depositional basins (grabens), coastal bays, and the position of peninsulas, barriers and capes. Tectonic uplift also has diverted a number of rivers which now drain into a barred megascale lake (Logan 1987). Only two rivers reach the sea to form deltas: the Gascoyne delta (Johnson 1982) and the Wooramel delta. In the Carnarvon Province, mangrove environments occur in different systems dependant on their geologic / tectonic setting: in small to large, protected to sheltered embayments cradled by the anticline structures where the geological grain of the uplift intersects the coast (Brown 1976, 1988; Fig 7); in delta settings; in inland coastal basins (Lake Macleod); in small inland depressions; and at the landward edge of prograded seagrass bank systems in front of the Pleistocene Boodalia delta (Davies 1970). Within these settings, the mangroves colonise tidal flats, tidal creeks, margins of spits, borders of lagoons, and the strandplains within the delta.

Boundaries between the coastal sectors

The nature of the boundaries and their relationship to geologic framework is only discussed here for the mainland sectors. The Rowley Shelf Province which stands clearly alone and distinct does not need clarification.

The boundaries between Cambridge Gulf and the Kimberley Coast, and between King Sound and the Kimberley coast are sharp and related to major boundaries in the geological systems. The boundary between the Canning Coast and King Sound is sharp and related to the shape of the gulf of King Sound, the influence of the Fitzroy River sediments, and the course of the Fitzroy River system. The boundary of the Canning Coast and the Pilbara Coast also is sharp; the Pilbara system begins with the first appearance of the Pilbara rivers (the De Grey) that brings with it to the coast terrigenous sands and muds; the first embayment (Cape Keraudren area) to the northeast of this river is a carbonate mud system.

The boundary of the Pilbara Coast with the Carnarvon Province requires further discussion. This boundary is placed at the southern centre of Exmouth Gulf where the last prominent ridge (Giralia Anticline; Logan *et al.* 1970) crops out to influence coastal topography: to the west of this ridge is the western shore of Cape Range with its system of mangrove-vegetated bays and lagoons, and to the east are broad mangrove-vegetated tidal flats (Yanrey Flats; Brown 1976). To the northeast of this ridge, the prominent tectonic terrain of the Carnarvon Province is subdued and buried by sediments of the coastal plain ribbon (Yannarie Coastal Plain; Beard 1975) of the Pilbara. Thus Exmouth Gulf is not viewed as an independant system for mangroves (*cf.* Semeniuk 1986b), but rather as a geographic gulf that straddles two separate coastal systems. The eastern shore of Exmouth Gulf, *i.e.*, Yanrey Flats, is grouped with the Pilbara Coast rather than within an "Exmouth Gulf system" because it forms the seaward edge of the Yanrey and Ashburton river drainages. The Yanrey Flats actually are contiguous with, and indistinguishable from the flats associated with the Ashburton and Cane rivers, and on this basis alone should be considered as part of the Pilbara Coast. Three additional features support this grouping. Firstly, the headwaters of the Yanrey River drain the rocky terrain of the Pilbara uplands (Geological Survey of Western Australia 1975), and has the morphology of a typical Pilbara river. Accordingly, the coastal part of this river should be grouped with other Pilbara rivers. The next river south of the Yanrey is diverted by the tectonics of the Carnarvon Province and empties into the north of Lake Macleod. Secondly, while the Yanrey River channel does not enter the sea with a conspicuous river mouth, as do the other prominent Pilbara rivers, examination of the delta lowlands reveals that the main channel of the Yanrey River bifurcates into numerous small channels that wind their way through, and locally are absorbed by, dune fields. The delta distributary channels *are* present, but are more diffuse and dissipated. Thirdly, the eastern shore of Exmouth Gulf is broadly lobate between the south-eastern part of Giralia Bay and Talandji (leeward of Tent Island); this lobate form is less pronounced but similar to the seaward margins of the other Pilbara river deltas (*e.g.*, Robe River and Fortescue River deltas).

Relationship to hinterland margin

The various mangroves systems and their habitats occur in clearly defined sectors related to hinterland geology (in part), coastal processes, and sedimentary provinces. The relationship of the hinterland margin to the tidal environment, a feature important in determining how fresh water is discharged into mangrove systems (Semeniuk 1983), also is linked to the sector setting, as the various sectors have differing types of contacts between the hinterland and tidal zone, varying from rock/colluvial, to dune, to limestone cliff, to alluvial plain (see Semeniuk 1983). For instance, the Kimberley ria coast with its high relief terrain and drainage channels has a variety of geomorphic and stratigraphic units such as alluvial fans and hinterland-margin (colluvium) sheets to facilitate fresh water discharges. The Canning Coast, in contrast, with its low-relief desert dune terrain, internal drainage and tidal embayment habitats, mostly does not contain the geomorphic and stratigraphic features to facilitate fresh water discharge. In addition, these two sectors are set in different climates, such that the availability of hinterland fresh water further contrasts them.

Discussion

The ensuing discussion develops comparisons with previous studies, delineates regions for mangroves in Western Australia, and provides a global significance to the Western Australian mangroves.

Comparisons with previous studies

The tropical coast of Western Australia has been previously described or classified by Jutson (1950), Carrigy & Fairbridge (1954), Davies (1977), Woods (1980), Galloway (1982), Gill (1982), Woods *et al.* (1985) and Semeniuk (1985, 1986a,b). The specific studies dealing with coastal classification, coastal sectors, and the distribution of mangrove habitats at subcontinental to regional scale are Woods (1980), Woods *et al.* (1985), Gill (1982), Galloway (1982), Thom (1982), and Semeniuk (1985, 1986).

Woods (1980) and Woods *et al.* (1985) divided the tropical Western Australian coast into four sectors based on regional geology, but the natural coastal sectors do not always correspond with the boundaries of basement geological units. In the Kimberley Block and the mobile zones that border its eastern and southern margins, the basement geological framework determines the disposition of these coastal sectors, but this is not the case for the boundaries of the natural coastal sector in the Pilbara region. Here the coastal plain (comprised of a sedimentary apron) formed down-stream from the Pilbara uplands. The seaward edge of the laterally continuous plain which forms the basis of the Pilbara coastal sector is comprised of alluvial fans, alluvial plains and deltas, and in fact it overlies three geological units and their contacts, *viz.*, the Pilbara block, the Carnarvon Basin and the Canning Basin.

Gill (1982) identified three sectors in the region of northwestern Australia and also noted their relationship to hinterland geology, but this classification is too simple and does not adequately address the variability of the Western Australian tropical coast.

Galloway (1982) recognised five coastal sectors, termed "mangrove regions", in tropical Western Australia as a framework to describing physiographic patterns of mangrove distribution in Australia generally. From south to north in Western Australia, these units were: Region 1—Northwest Cape to Cape Keraudren; Region 2—Cape Keraudren to Cape Leveque; Region 3—Cape Leveque to Point Usborne; Region 4—Point Usborne to Cape Dussejour; and Region 5—Cape Dussejour to Point Pearce. I am largely in agreement with the location of four of the regions of Galloway (1982), *i.e.*, the sectors of Cambridge Gulf, Kimberley Coast, King Sound and Canning Coast of this paper coincide with Galloway's regions. However, I do not agree with the Cape Keraudren to Northwest Cape Sector of Galloway, because it agglomerates the entire Pilbara Coast with a portion of the system associated with the western shore of Exmouth Gulf. Galloway (1982) does not recognise the mangroves in the Carnarvon Province as a mangrove region, nor the islands of the Rowley Shelf. The correlation of the coastal sectors as outlined in this paper with those of Galloway (1982) is outlined in Table 2.

Table 2

Comparison of the coastal regions of Galloway (1982) with this study

This study	Galloway (1982)
Cambridge Gulf	part of Cape Dussejour to Point Pearce
Kimberley Coast	Point Usborne to Cape Dussejour
King Sound	Cape Leveque to Point Usborne
Canning Coast	Cape Keraudren to Cape Leveque
Pilbara Coast	part of Northwest Cape to Cape Keraudren
Rowley Shelf	not recognised
Carnarvon Province	not recognised

Thom (1982) outlined five regional-scale types of coast in Australia within which mangroves occur: river-dominated allochthonous systems (mainly deltas); tide-dominated allochthonous systems (mainly deltaic); wave-dominated allochthonous systems (barriers and lagoons); composite river- and wave-dominated systems (of alluvial plains, deltas, and barriers); and drowned bedrock valleys (rias and alluvial plains). Thom (1982) emphasised that allochthonous sediments were brought to the coast to develop coastal landforms as habitat settings for mangroves under conditions that were river-, wave-, or tide-dominated (his Figure 1.1 illustrates the recurring pattern of a river or fluvial channel supplying the allochthonous material to the shore); this sedimentary material would then be shaped by coastal processes into the basic coastal types to form the framework for mangrove habitats. Many of the coast types of Thom (1982) can be recognised in the study area of this paper, but in detail the coast of tropical Western Australia has been subdivided differently here because diverse processes have operated and consequently more varied regional-scale mangrove systems have formed. For instance, some of the large bays in northwestern Australia have not formed by marine inundation of bedrock, but by inundation of a dune hinterland; some of the sediments are allochthonous, but have been derived from a local dune field; some areas are comprised of autochthonous sediments (*viz.*, the carbonate suite); some coastal landforms are inherited from the Pleistocene (*viz.*, the Pleistocene limestone barriers); in some cases of beach / dune coasts, the setting is not related directly to a fluvial source, but represents the down-drift accumulation of coastal sand, or represents the reworking of older deposits; marine inundation in some areas has developed not only drowned bedrock valleys (rias) but also archipelagos, and locally, just isolated bedrock islands. Also the islands of the Northwest Shelf, formed as residual Pleistocene aeolian units, or as faulted outliers, or as emergent, shoaled Holocene deposits are not readily classified in the scheme of Thom (1982).

In contrast, this study places emphasis on the variety of regional-scale landforms, such as active deltas (and whether they were wave- or tide-dominated), inactive (destroyed) deltas, Pleistocene barrier islands, pre-Holocene, and perhaps even pre-Quaternary ancestral landforms, embayments, various types of islands, amongst others. As described above, the main regional-scale systems that form settings for mangroves in Western Australia are wave-dominated deltas, tide-dominated deltas, barrier island systems, embayments, ria shore and archipelago systems, dune coasts, lagoon systems of various origins, and island complexes.

Semeniuk (1986b) identified four main types of coast for mangrove habitats at the regional scale: ria shores and archipelagos; deltas and barrier islands; sheltered bay / embayments; and gulfs; and showed their distribution along the coast of tropical Western Australia. The present study shows that the mangrove systems in Western Australia are more varied and complex than that outlined in that earlier study (*op. cit.*). Exmouth Gulf was also recognised by Semeniuk (1986b) as a distinct mangrove coastal type as part of the "gulf settings" that included King Sound, Cambridge Gulf, and Exmouth Gulf, whereas Exmouth Gulf is not identified here as a coastal system akin to King Sound, but rather as a geographic entity that straddles two separate systems.

Delineating mangrove regions

Mangrove habitats of tropical Western Australia occur in well defined sectors with differing coastal geomorphology and coastal processes, and identifying such sectors is one approach to the delineation of mangrove regions in Western Australia. Identification of the sedimentary province also is important in the definition of mangrove habitats: simple carbonate mud environments, such as along the Canning Coast, where there is no marked high-tidal facies differentiation for instance, provide different habitats to those areas that present a profusion of facies, such as the ria shores along the Kimberley coast. These types of coastal differences should be recognised in separating mangrove systems. On the basis of sediment differences alone, the mangrove systems of tropical Western Australia could be classed into several major regions.

The combination of coastal geomorphology and sedimentary provinces forms the basis of delineating the mangrove systems of this paper, and with this approach seven systems of mangrove environments have been identified. However, this approach does not involve the biogeography of mangroves, and so some system of combining biogeography and physical factors is required if the natural mangroves regions are to be recognised.

Biogeographically, mangrove regions have been delineated to date either on a combination of biological and climatic criteria (Semeniuk *et al.* 1978), or on biological criteria alone (Bridgewater 1982, 1985). Semeniuk *et al.* (1978) related the mangrove systems and species richness in Western Australia to climate, using the climate boundaries of Thornthwaite (1933; cited in Gentilli 1972). Within the tropical zone were three biogeographic regions: humid to subhumid (Biogeographic Region I) with 15 mangrove species; semiarid (Biogeographic Region II) with 12 species; and arid (Biogeographic Region III) with six species.

Bridgewater (1982, 1985) applied mathematical methods to delineate mangrove regions in Western Australia on species occurrence and abundance, and obtained different biogeographic boundaries to Semeniuk *et al.* (1978).

Combining the geomorphic-sedimentary sectors (which determine whether habitats for particular species will be developed) with climate (which determines species richness) probably provides the best method to define mangrove regions (as distinct from biogeographic regions) in Western Australia. Thus mangrove regions are delineated on the availability of appropriate habitats and species richness. This approach is useful in Western Australia, especially since it is apparent that some sectors described above are restricted to specific climates. For example, ria shores with their variety of habitats at small and medium scales, and their range of geomorphic/stratigraphic mechanisms that facilitate fresh water discharge, are located in the more humid parts of Western Australia. Limestone barrier islands, with less abundant systems for discharging fresh water, fortuitously occur in arid parts of Western Australia, where fresh water is scarce anyway.

The delineation of geomorphic-sedimentary regions is relatively simple, since the various coastal systems appear to have sharp boundaries. The delineation of climate regions, however, is not so simple. As discussed by Gentilli (1972), climate can be classified using different emphases, and climate maps can be constructed for different purposes.

Within mangrove regions, where climate influences the salinity of soils and the physiology and structure of the vegetation, the important climatic parameters would appear to be rainfall, evaporation, temperature, and wind. However, although wind is important in the sedimentological development of habitats for evaporation on tidal flats and in the physiologic stress it places on plants, it is with difficulty that it can be incorporated into integrated climate maps, and two of its more important effects, *viz.*, inducing evaporation to develop saline soils, and inducing transpiration within vegetation, are incorporated in the parameter of evaporation. Climatic regions delineated by integrating the parameters of rainfall, evaporation and temperature thus would appear to be the most useful in analysing and comparing the different mangrove regions.

Choosing a climate map to link with mangrove studies, however, remains a problem. To date there has not been a map generated that adequately integrates the parameters of rainfall, temperature and evaporation suitable for mangrove studies. The most useful maps are those of Thornthwaite (1933, cited in Gentilli 1972), showing climatic regions; Koppen (1936), also showing climatic regions; Gentilli (1972), showing moisture regions as determined by rainfall and temperature; and McBoyle (1973), showing climatic regions as determined by factor analysis of some 20 climate parameters. While in principle the best approach to categorising climate is that of McBoyle (1973), who carried out factor analysis of a range of climatic parameters to give rational boundaries to climate regions on criteria other than vegetation and soils, the results of McBoyle (1973) are not directly useful to mangrove studies in Western Australia. Firstly, only six climate stations are used in the analysis for the whole of the northwestern coastal region; secondly, because evaporation is not used in the analysis; thirdly, many of the 20 parameters are not directly related to mangrove systems. The systems of Thornthwaite (1933, cited in Gentilli 1972) and Koppen (1936) essentially show the same location of humid, semi-arid and arid regions along the coast. The humid area is sited on the region of the Mitchell Plateau in the Kimberley region; the semi-arid area is sited on the region of Dampier Peninsula-Roebuck Bay, King Sound, Cambridge Gulf, and northeast and southeast extremities of the Kimberley Coast; the arid area is sited on the region of the the middle to southern part of the Canning Coast, and all the coast from there to Shark Bay. The system of Gentilli (1972) is essentially similar to Thornthwaite (1933) and Koppen (1936) for coastal regions, but Cambridge Gulf is not classed as the same climate as King Sound.

For purposes of this paper, following the boundaries of Thornthwaite (1933, cited in Gentilli 1972) and Koppen (1936), the three climate regions are: humid/subhumid in the central Kimberley Coast (centred on the Mitchell Plateau area); semi-arid in the areas of Cambridge Gulf, King Sound, northeast and southeast extremities of the Kimberley Coast, the Dampier Peninsula-Roebuck Bay, and the Canning Coast to as far south as Cape Bossut; and arid in the area between Cape Bossut to Shark Bay, encompassing the southern part of the Canning Coast, and all of the Pilbara Coast, the Rowley Shelf Province and the Carnarvon Province.

This method of combining the coastal sectors with climate provides nine major mangrove regions in Western Australia:

1. Cambridge Gulf — semiarid zone.
2. Kimberley Coas — humid/subhumid zone;
3. Kimberley Coast — semiarid zone;
4. King Sound — semiarid zone;
5. Canning Coast — semiarid zone;
6. Canning Coast — arid zone;
7. Pilbara Coast — arid zone;
8. Rowley Shelf Province — arid zone;
9. Carnarvon Province — arid zone.

Most of the regions correspond to the geomorphic-sedimentary sectors, but some sectors encompass two types of climate setting: the Kimberley Coast has two climate types, and the Canning Coast has two climate types. As such, this pattern provides some insight into the regional controls in the elimination of some species of mangroves to southwards within these sectors, because while the climate is changing, the habitat types are similar from one end of the sector to the other. For example, consider the areas of Cape Bossut and Cape Keraudren: the coastal systems and mangrove habitats at both these areas are similar—they are part of the Canning Coast sector with similar arrangement of a limestone barrier protecting an embayment, and both have carbonate mud in the mangrove zone, but Cape Bossut is in the semi-arid part of the Canning Coast, and Cape Keraudren is in the arid part. Cape Bossut has the following common mangrove species: *A. annulata*, *A. corniculatum*, *A. marina*, *B. exaristata*, *C. schultzii*, *C. tagal*, *R. stylosa* and *S. alba*. Cape Keraudren has the following mangrove species: *A. annulata*, *A. corniculatum*, *A. marina*, *B. exaristata*, *C. tagal*, *R. stylosa* and *O. ctodonta*, with the species representative of more northerly areas, *viz.*, *C. schultzii* and *S. alba*, absent.

Global significance of mangrove systems in Western Australia

In general, to assess the significance of mangroves globally it is necessary to determine the species richness of various regions, and the variability of coastal style (habitat setting) where mangroves are located. In order to assess the global significance of mangrove formations specifically in Western Australia, the discussion that follows centres on several inter-related aspects of their subcontinental to regional features: species pool, habitats, climate setting and processes (and specifically in this case the arid zone setting and processes), and inter-relationship of mangrove systems across the climate cline and the geological / geomorphic provinces.

The mangroves of northwestern Australia belong to the Eastern Group (=Old World) of mangroves, centred on the Indian-Pacific Ocean area (Tomlinson 1986), and within this region, they more specifically belong to the Indo-Malesian Group that encompasses Pakistan, India, Burma, Malaysia, Indonesia, Celebes, northern Australia and Papua-New Guinea (Chapman 1977). This Indo-Malesian group is the most species-rich region of mangrove worldwide (Chapman 1976). Within this grouping, however, northern Australia is part of the Northern Australian-Papuan sub-group, being less species-rich than some of the other sub-groups but having some species features unique to that region (Chapman 1977).

In terms of endemism and restricted species, Western Australia does not support any unusual, endemic, or restricted mangrove species. In fact, all mangrove species within Western Australia are common and widespread elsewhere either in northern Australia, or in the Indo-Pacific region proximal to northern Australia, and so in this sense, the mangroves of Western Australia are not globally significant. However, what Western Australia does provide that is of global significance is its richness and variability of habitats for mangroves, from large to small scale, as within the same subcontinent there are major variations in style of coast, oceanographic setting, and climate, that interplay with the regional mangrove species pool. This results in a representative record of variation in species, assemblages, structures and physiognomy which provides excellent case studies of biological response to the physico-chemical environment, and valuable information on their biogeographic patterns.

Locations elsewhere in the world may contain the same type of habitats as in Western Australia, but these tend to be scattered. For instance, mangrove formations are well developed in the deltas of the Niger river and the Ganges river, and in the ria coastal settings of the Malaysian region; but Western Australia presents a wider range of habitats for mangroves at the large to small scale in a relatively shorter tract of coast because the geologically and geomorphically diverse coastline traverses several climatic and oceanographic regions. Here, as described in this paper, the variable coasts, that range from tide-dominated rias to wave-dominated deltas and barriers, span a climate gradient from humid to arid. Where there are extensive tracts of mangrove elsewhere, the habitats are either relatively uniform by comparison to Western Australia, or relatively species-poor. Chapman (1977), for instance, provides a map of the global distribution of mangroves from which it is apparent that the tracts of coast that are of similar or greater length than that of the northwestern part of Australia are in relatively species-poor regions of the globe, *e.g.*, the west and east coast of Africa and the Gulf of Mexico. However, in contrast, species-rich areas, such as those situated in the Malaysian archipelago, exhibit less coastal variation in their mangrove habitats than those of Western Australia. There are two reasons for this. Firstly, the Malaysian archipelago is island-dominated and centred on the equator, and the climate is ubiquitously tropical humid with little scope for the development of arid-style hinterland or arid-zone-influenced coastal landforms (Trewartha 1968). Secondly, many of the island landforms are high relief because the area is an island arc complex, located on a collision zone between two tectonic plates (Forsyth & Uyeda 1975), and volcanism, tectonism and uplift are prevalent (Uyeda 1978)—consequently many of the coastal landforms are of the ria / archipelago or gulf type.

One of the most species-rich areas for mangroves is in India, but this subcontinent does not present a continuous stretch of mangrove coast within which the various regional gradients could be viewed as well as that in northwestern to northern Australia. Also in India there is a large anthropogenic influence resulting in alteration and destruction of mangroves.

Small-scale features within a given coastal system also provide important information on mangroves and their physical setting. In this regard, the arid coastal setting of the Pilbara region is of global significance, compared to other coasts of similar tropical aridity worldwide, such as the Somalia coast, the Persian Gulf, the Red Sea and Arabian Peninsula coast, the Pakistan coast, the Namibian coast and the northwest African coast, Baja California, and the Peruvian-Chilean coastline (Semeniuk 1993). The literature suggests that most of the tropical coasts that are in an equivalent arid setting to the Pilbara are dominantly of the steep or cliffed rocky shore type, where headlands separate bays and sandy coastal stretches, or are of the aeolian type, or are low gradient sabhka type. Many of those arid coasts that resemble the Pilbara, in their setting and their configuration of alluvial, deltaic and aeolian facies within a coastal plain formed down-slope from a high-relief upland, in fact are tectonic. In the Pilbara, the Quaternary coastal development has not been significantly uplifted, if at all. Hence the complication of tectonics has not disrupted the geomorphic pattern, and the various ensembles of Quaternary sediments are still inter-related in time and space. With subsidence and burial, those sediments that have accumulated in the coastal zone will form a distinct assemblage of stratigraphic units, inter-related synoptically and across unconformities, thus providing a physical framework of coastal types and stratigraphic / hydrologic styles where mangrove habitats can develop. This would suggest that the style of sedimentation and stratigraphic evolution of the Pilbara coastal system is indeed a globally different and useful model of coastal form in an arid setting. It is this very same coastal system that hosts mangroves and also forms the arid zone end of a biogeographic continuum traceble from the more humid areas in the north.

Mangroves of northwestern Australia should be viewed as a continuation of the northern Australian system which incorporates the area from Cambridge Gulf to Darwin, and as part of the climatic cline extending from there into the

Papuan region. There are two significant aspects to this. Firstly, in this context, the variety of large-scale coastal habitat settings of the Western Australian coast can be viewed as significant in that it contrasts with other styles of coasts developed further north in Australia and in the Papuan to Malaysian archipelago settings, which have a predominance of steep shores, high-tidal deltas and ria coastal types (Coleman *et al.* 1970; Bird & Schwartz 1985). This allows researchers to trace the changes in mangrove formations from humid macrotidal zones into arid and microtidal regions, albeit against a changing coastal style, and also from one coastal style (and its smaller scale habitats) to another within the same climatic setting (*e.g.*, ria setting *vs.* barrier island setting vs. deltaic setting) in order to compare the differing effects of habitats and climate on mangrove systems. Secondly, the Malesian-Papuan-Northern Australian mangroves form a group that extends far into the higher latitudes. Within this group, the Western Australian coast, being the most arid coast in Australia, uniquely carries the cline of mangrove changes from humid, to semi-arid to arid within a system that globally is the most species-rich mangrove region. In contrast, other coasts in equivalent latitudes, *e.g.*, Southern Africa and South America, are situated in relatively species-poor regions.

The tropical coast of northwestern Australia thus provides an important scientific resource for present and future researchers, and a model for mangrove biogeography and ecology that is useful globally in that it combines within the one coastal tract many aspects of regional scale features found scattered in other parts of the world. In this regard, I consider it to be an excellent and valuable natural laboratory of international significance.

References

Beard J S 1967 An inland occurrence of mangroves. The Western Australian Naturalist 10:112-115.

Beard J S 1975 The vegetation of the Pilbara area. Explanatory notes to Map Sheet 5 of Vegetation Survey of WA: Pilbara. University of Western Australia Press, Nedlands.

Bird E C F & Schwartz M L 1985 The world's coastline. Van Nostrand Reinhold, New York.

Bridgewater P B 1982 Mangrove vegetation of the southern and western Australian coastline. In: Mangrove ecosystems in Australia: structure, function and management (ed B F Clough) AIMS & ANU Press, Canberra, 111-120.

Bridgewater P B 1985 Variation in the mangal along the west coastline of Australia. Proceedings of the Ecological Society of Australia 13:243-256.

Brown R G 1976 Exmouth Gulf. In: Carbonate sediments of the West Coast of Western Australia (eds B W Logan, R G Brown & P G Quilty) 25th International Geological Congress, Sydney, 55-75.

Brown R G 1988 Holocene sediments and environments, Exmouth Gulf, Western Australia. In: The North West Shelf (eds P G & R R Purcell) Proc. Petroleum Exploration Society Australia Symposium, Perth, 85-93.

Bunt J S & Williams W T 1980 Studies in the analysis of data from Australian tidal forests ("mangroves"). I. Vegetational sequences and their graphic representation. Australian Journal of Ecology 5:385-390.

Bureau of Meteorology 1973 The Climate and Meteorology of West. Australia. In: Western Australian Year Book 12, Melbourne, 25-59.

Bureau of Meteorology 1975 Climatic averages Western Australia. Australian Government Publishing Service, Canberra.

Calder M 1979 Australian National Tide Tables 1980 Australian Hydrographic Publication II. Australian Government Publishing Service, Canberra.

Carrigy M A & Fairbridge R W 1954 Recent sedimentation, physiography and structure of the continental shelves of Western Australia. Journal of the Royal Society of Western Australia 38:65-95.

Chapman V J 1976 Mangrove Vegetation. Cramer, Lehre.

Chapman V J 1977 Introduction. In: Ecosystems of the World. 1. Wet Coastal Ecosystems (ed V J Chapman) Elsevier, Amsterdam, 1-29.

Coleman F 1971 Frequencies, tracks and intensities of tropical cyclones in the Australian region, Nov. 1909-June 1969. Bureau of Meteorology, Australian Government Publishing Service, Canberra.

Coleman J M, Gagliano S M & Smith W G 1970 Sedimentation in a Malaysian high tide tropical delta. Society of Economic Palaeontologists and Mineralogists Special Publication 15:185-197.

Davie J D S 1985 The mangrove vegetation of the South Alligator River, Northern Australia. In: Coasts and tidal wetlands of the Australian monsoon region (eds K N Bardsley, J D S Davie & C D Woodroffe) NARU, Australian National University, Mangrove Monograph No. 1, 133-151.

Davies G R 1970 Carbonate bank sedimentation eastern Shark Bay, Western Australia. In: Carbonate sedimentation and environments, Shark Bay, Western Australia. American Association of Petroleum Petrologists Memoir 13, 85-168.

Davies J L 1977 The coast. In: Australia, a geography (ed D N Jeans) Sydney University Press, Sydney, 134-151.

Easton A K 1970 The tides of the continent of Australia. Horace Lamb Centre Oceanographic Research, Flinders University, South Australia, Research Paper No. 37.

Forsyth D & Uyeda S 1975 On the relative importance of the driving forces of plate motion. Geophysical Journal 43:163-200.

Galloway R W 1982 Distribution and physiographic patterns of Australian mangroves. In: Mangrove ecosystems in Australia: structure, function and management (ed B F Clough) AIMS & ANU Press, Canberra, 31-54.

Gentilli J 1971 Climates of Australia and New Zealand. World Survey of Climatology 13, Elsevier, Amsterdam.

Gentilli J 1972 Australian Climate Patterns. Nelson, Melbourne.

Geological Survey of Western Australia 1975 The geology of Western Australia. Geological Survey of Western Australia Memoir 2, Perth.

Gill E D 1982 Eight coasts of Australia. CSIRO Division of Applied Geomechanics, Technical Report 119, Mt. Waverley, Vic.

Jennings J 1975 Desert dunes and estuarine fill in the Fitzroy estuary, northwestern Australia. Catena 2:215-262.

Jennings J & Bird E C 1967 Regional geomorphological characteristics of some Australian estuaries. In: Estuaries (ed G H Lauff) American Association for the Advancement of Science, Washington D.C., 121-128.

Johnson D P 1982 Sedimentary facies of an arid zone delta: Gascoyne delta, Western Australia. Journal of Sedimentary Petrology 52:547-563.

Jutson J T 1950 The physiography (geomorphology) of Western Australia. Western Australian Geological Survey Bulletin 95, Perth.

Koppen W 1936 Das Geographische System der Klimate. Vol 1C, In: Handbuch der Klimatologie (W Koppen & R Geiger). Berlin.

Logan B W 1987 The MacLeod evaporite basin, Western Australia. American Association of Petroleum Geologists Memoir 44, Tulsa, Oklahoma.

Logan B W, Read J F, & Davies G R 1970 History of carbonate sedimentation, Quaternary Epoch, Shark Bay, Western Australia. In: Carbonate sedimentation and environments, Shark Bay, Western Australia. American Association of Petroleum Geologists Memoir 13, p. 38-83, Tulsa, Oklahoma.

Lourensz R S 1981 Tropical cyclones in the Australian region, July 1909 to June 1980. Bureau of Meteorology, Australian Government Publishing Service, Canberra.

Lugo A E & Snedaker S C 1976 The ecology of mangroves. Annual Reviews of Ecology & Systematics 5:39-64.

MacNae W 1968 A general account of the fauna and flora of mangrove swamps and forests in the Indo-West-Pacific region. Advances in Marine Biology 6:73-270.

McBoyle G R 1973 Climatic classification of Australia by computer. Australian Geographical Studies IX:1-14.

Milton D 1978 The rainfall from tropical cyclones in West Australia. Geowest. Working Papers, Department of Geography, University of Western Australia 13, 61p.

Saenger P, Specht M M, Specht R L & Chapman V J 1977 Mangal and coastal salt marsh communities in Australasia. In: Ecosystems of the World. 1. Wet Coastal Ecosystems (ed V J Chapman) Elsevier, Amsterdam, 293-345.

Semeniuk V 1980a Mangrove zonation along an eroding coastline in King Sound, North-Western Australia. Journal of Ecology 68:789-812.

Semeniuk V 1980b Quaternary stratigraphy of the tidal flats King Sound, Western Australia. Journal of the Royal Society of Western Australia 63:65-78.

Semeniuk V 1981a Long-term erosion of the tidal flats King Sound, North-Western Australia. Marine Geology 43:21-48

Semeniuk V 1981b Sedimentology and the stratigraphic sequence of a tropical tidal flat, North-Western Australia. Sedimentary Geology, 29:195-221

Semeniuk V 1982 Geomorphology and Holocene history of the tidal flats, King Sound, North Western Australia. Journal of the Royal Society of Western Australia 65:47-68.

Semeniuk V 1983 Regional and local mangrove distribution in Northwestern Australia in relationship to freshwater seepage. Vegetatio 53:11-31.

Semeniuk V 1985 Development of mangrove habitats along ria coasts in north and northwestern Australia. Vegetatio 60:3-23.

Semeniuk V 1986a Terminology for geomorphic units and habitats along the tropical coast of Western Australia. Journal of the Royal Society of Western Australia 68:53-79.

Semeniuk V 1986b Threats to, and exploitation and destruction of, mangrove systems in Western Australia In: Mangrove Ecosystems of Asia and the Pacific; status, exploitation and management (eds C D Field & A J Dartnall) Proceedings Research for Development Seminar, Australian Institute of Marine Science, Townsville, 228-240.

Semeniuk V 1993 The Pilbara coast: a riverine coastal plain in a tropical arid setting, Northwestern Australia In: Late Quaternary evolution of coastal and lowland riverine plains of southeast Asia and northern Australia (ed C D Woodroffe) Sedimentary Geology 83:235-256

Semeniuk V & Wurm P A S 1987 Mangroves of the Dampier Archipelago, Western Australia. Journal of the Royal Society of Western Australia 69:29-87.

Semeniuk V, Chalmer P N & LeProvost I 1982 The marine environments of the Dampier Archipelago: Journal of the Royal Society of Western Australia 65:97-114.

Semeniuk V, Kenneally K F & Wilson P G 1978 Mangroves of Western Australia. Handbook 12, Western Australian Naturalists Club, Perth.

Specht R L 1981 Foliage protective cover and standing biomass. In: Vegetation classification in Australia (eds A N Gillison & D J Anderson) CSIRO & ANU Press, Canberra.

Steedman R K 1985 Air quality meteorology of the Burrup Peninsula, Western Australia, June 1982 to December 1984. Vol.1 text and appendices A to G. RK Steedman Ltd. Report No. R271 Aug 1985. Unpublished Report to Woodside Offshore Petroleum Ltd.

Steedman R K & Colman E J 1985 On the joint probability of extreme winds, waves and currents at North Rankin 'A', north western Australia. In: The application of joint probability of Metocean phenomena in the oil industry's structural design work. The Oil Industry International Exploration & Production Forum, London, Paper 1, 20p.

Thom B G 1967 Mangrove ecology and deltaic geomorphology: Tabasco, Mexico. Journal of Ecology 55:301-343.

Thom B G 1982 Mangrove ecology—a geomorphic perspective. In: Mangrove ecosystems in Australia: structure, function and management (ed B F Clough) AIMS & ANU Press, Canberra, 301-343.

Thom B G, Wright L D & Coleman J M 1975 Mangrove ecology and deltaic-estuarine geomorphology. Journal of Ecology 63:203-232.

Tomlinson P B 1986 The botany of mangroves. Cambridge University Press, Cambridge.

Trewartha G T 1968 An introduction to climate. McGraw-Hill, New York.

Uyeda S 1978 The new view of the earth. W H Freeman & Co., San Francisco.

Wells A G 1981 A survey of riverside mangrove vegetation fringing tidal river systems of Kimberley, Western Australia. In: Biological Survey of Mitchell Plateau and Admiralty Gulf, Western Australia. Western Australian Museum Supplement No 3, 95-121.

Wells A G 1982 Mangrove vegetation of northern Australia. In: Mangrove ecosystems in Australia: structure, function and management (ed B F Clough) AIMS & ANU Press, Canberra 57-78.

Woods P G 1980 Coastal management in Western Australia. Department of Conservation & Environment Bulletin 49, Perth.

Woods P G, Webb M J & Eliot I G 1985 Western Australia In: The World's Coastline (eds E C F Bird & M L Schwartz) Van Nostrand Reinhold, New York, 929-947.